



D5.2

V2X-based cooperative sensing and driving in Transition Areas

Project Acronym	TransAID	
Project Title	Transition Areas for Infrastructure-Assisted Driving	
Project Number	Horizon 2020 ART-05-2016 – GA Nr 723390	
Work Package	WP5	Connectivity and Signalling
Lead Beneficiary	Universidad Miguel Hernandez (UMH)	
Editor / Main Author	Alejandro Correa	UMH
Reviewer	Robbin Blokpoel	DYN
Dissemination Level	PU	
Contractual Delivery Date	28/02/2019 (M18)	
Actual Delivery Date	08/07/2019	
Version	v1.1	



This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 723390.

Document revision history

Version	Date	Comments
v0.1	2018-11-24	Initial structure of document
v0.2	2019-01-14	Include draft state of the art and triggering conditions of cooperative sensing
v0.3	2019-01-16	Sensors state of the art and TransAID sensor fusion approaches
v0.4	2019-01-18	Message flows of service 1
v0.5	2019-01-21	DLR in-vehicle sensor processing and minor corrections in existing text
v0.6	2019-01-22	Message flow of services 2 and 3
v0.7	2019-01-23	Message flow of service 4
v0.8	2019-01-24	Message flow of service 5
v0.9	2019-01-28	Extended sensor fusion at the infrastructure
v0.10	2019-01-29	Review of message flows of the services and added cooperative lane change section
v0.11	2019-02-13	State of the art of cooperative manoeuvres included in Section 3
v0.12	2019-02-15	Added analysis of MCM generation rules in Section 3
v0.13	2019-02-15	Updated Section 2
v0.14	2019-02-18	Introduction and Conclusions
v0.15	2019-02-19	Section 2.2.1.2 added
v0.16	2019/02/19	Review of all the document
v0.17	2019/02/25	Internal quality review
v1.0	2019/02/26	Final version
v1.1	2019/07/08	Update after official review

Editor / Main author

Alejandro Correa (UMH)

List of contributors

Franz Andert (DLR)

Robbin Blokpoel (DYN)

Nicolai Wojke (DLR)

Gokulnath Thandavarayan (UMH)

Baldomero Coll (UMH)

Miguel Sepulcre (UMH)

Javier Gozalvez (UMH)

Anton Wijbenga (MAP)

Julian Schindler (DLR)

Sven Maerivoet (TML)

List of reviewers

Robbin Blokpoel (DYN)

Dissemination level:

■ PU : Public

☐ RE : Restricted to a group specified by the consortium (including the Commission Services)

☐ CO : Confidential, only for members of the consortium (including the Commission Services)

Table of contents

Document revision history	2
Table of contents	4
Executive Summary	6
1 Introduction	8
1.1 About TransAID	8
1.2 The TransAID iterative approach	8
1.3 Purpose of this document	9
1.4 Structure of this document	10
1.5 Glossary	10
2 Cooperative Sensing	13
2.1 State of the art	15
2.1.1 Sensor information	15
2.1.1.1 In-vehicle sensors	15
2.1.1.2 Infrastructure-mounted sensors	16
2.1.1.3 Sensor fusion	19
2.1.2 Existing studies on collective perception	23
2.1.2.1 ETSI Collective Perception Service	24
2.2 TransAID Sensor Fusion	29
2.2.1 Sensor fusion at the infrastructure	29
2.2.1.1 Sensor fusion for motorway approach models	29
2.2.1.2 Enabling sensor fusion with road-side camera infrastructure	32
2.2.2 Sensor fusion at the vehicle	37
2.3 Performance evaluation of ETSI Collective Perception	38
2.3.1 Operation	40
2.3.2 Communications performance	42
2.3.3 Perception capabilities	43
3 Cooperative Driving	49
3.1 State of the art	49
3.1.1 ETSI approach on manoeuvre coordination	51
3.1.2 TransAID proposal	52
3.2 Message flow for the TransAID services	53
3.2.1 Message flow common to all TransAID services	53
3.2.2 Service 1: Prevent ToC/MRM by providing vehicle path information	54

3.2.3	Service 2: Prevent ToC/MRM by providing speed, headway and/or lane advice	56
3.2.4	Service 3: Prevent ToC/MRM by traffic separation	58
3.2.5	Service 4: Manage MRM by guidance to safe spot	60
3.2.6	Service 5: Distribute ToC/MRM by scheduling ToCs.....	63
3.3	Cooperative lane changes at Transition Areas	65
3.4	Preliminary analysis of MCM generation rules	67
4	Conclusions.....	73
	References.....	75
	Annex A: List of contributions to V2X standardization and specification.....	79

Executive Summary

The objective of the TransAID (Transition Areas for Infrastructure-Assisted Driving) project is to deal with situations that cooperative and automated vehicles (CAV) might face when they are approaching to traffic conditions or zones that their automated systems are not able to handle by themselves. In those cases, the driver will be required to take control of the vehicle; this is the so-called Transition of Control (ToC). TransAID develops and demonstrates traffic management procedures and protocols to increase the overall traffic safety and efficiency specially at transition areas (i.e. zones where ToCs should take place) considering the coexistence of CAVs, autonomous vehicles (AVs), cooperative vehicles (CVs) and legacy vehicles (LV). TransAID measures require the use of communications between vehicles (V2V), and between vehicles and the road infrastructure (V2I) which are mainly used to gather information about the traffic stream through cooperative sensing and to support in the coordination of the vehicles maneuvers through cooperative maneuvers. In this context, this document shows the sensor devices and techniques to fuse their data that are being developed in TransAID. This includes techniques implemented at camera-equipped infrastructures that are able to detect, create bounding boxes and uniquely track objects using optical flow, and at the vehicle employing a hybrid sensor fusion strategy which contains a low-level LIDAR fusion module, that transforms the sensor data of multiple laser scanners into a common coordinate system, and an object-level fusion module, that fuses in-vehicle sensor data with data coming from neighbouring vehicles. The document also shows the cooperative techniques that are being designed to enable the Collective Perception Service (CPS) in line with ETSI. The ETSI's CPS entails the continuous exchange of Collective Perception Messages (CPM) that include a logic representation of the objects detected by the sensors and which are useful to improve the vehicles' and the infrastructure's perception of the driving environment. A key aspect for the efficient execution of the CPS is the definition of appropriate generation rules for the transmission of the CPMs, i.e. how often they are transmitted and what information do they include. This document includes a comprehensive analysis of the effect on the communications performance and information awareness of different CPM generation rules that are being considered in ETSI. In particular, the CPM generation rules follow a periodic policy (at 10Hz or 2Hz) where all detected objects are included, or a dynamic one where only the objects fulfilling some requirements are included. The conducted analysis has shown that there is a trade-off between perception capabilities and communications performance/scalability: vehicles detecting the same object(s) and including them in their CPMs create redundant detection which can help improve the perception capabilities but generate higher channel load levels and therefore impact the performance of V2X networks. The obtained results show that the ETSI's dynamic generation policy significantly reduces the communications channel load compared with the periodic ones, without compromising the perception capabilities. In the framework of TransAID, advanced policies will be proposed to further optimize the CPM, both its content and transmission triggering conditions, in order to achieve the necessary levels of redundancy and minimize the impact of the implementation of CPM in the stability and scalability of future V2X networks. In addition, this document investigates existing cooperative driving mechanisms, and specially the ETSI approach on manoeuvre coordination. The ETSI's Manoeuvre Coordination Service (MCS) is defining new concepts and messages which can be used to coordinate manoeuvres between vehicles. TransAID is actively participating in this process, e.g., by means of the definition of the Manoeuvre Coordination Message (MCM) and extending the role of the infrastructure to support the vehicles' manoeuvres coordination under certain scenarios and conditions. In this context, this document presents the message flow for the set of services that are being considered in TransAID. First, this document has analysed the traffic management measures defined by the different services of the TransAID project, and the required message flow for each service has been defined. Each message flow describes how, when, and where the vehicles communicate between them, and between them

and the infrastructure, to execute the traffic management measures. Then, this document provides a preliminary analysis of the MCM generation rules. As highlighted for the CPMs, MCM messages should be transmitted with a frequency high enough to guarantee that the vehicles' manoeuvre coordination is possible. However, a too frequent exchange of MCM messages can increase the channel load to the point that it can negatively impact the performance and scalability of the V2X network. The conducted analysis has shown the importance of considering the vehicular context for the generation of the MCM messages in order to achieve a good balance between channel load and reliability for a safe execution of the cooperative manoeuvres.

1 Introduction

1.1 About TransAID

The introduction of Automated Vehicles (AVs) is expected to improve traffic safety, reduce fuel consumption and improve traffic efficiency. To do so, automatization of perception and control tasks is employed with the aim of outperforming the capabilities of human drivers. The efforts of the automotive industry are focused on preparing future AVs to support an increasing number of road conditions and traffic situations. However, there will be situations where the automated systems will reach their functional limits and will not be able to handle specific traffic situations on their own [1]. In these situations, a Transition of Control (ToC) to manual driving will be required. The duration of a ToC will be influenced by the time required by the driver to recover full situation awareness and safely take over control of the vehicle. This time increases in higher automation levels, where drivers are allowed to perform non-driving related secondary tasks. If the driver is not able to take over control of the car, the automated vehicle will perform a so-called Minimum Risk Manoeuvre (MRM) to bring the vehicle into a safe spot (e.g. decelerating to full stop, or change lane to occupy a safe spot [2]. There will be areas and situations on the roads where high automation can be granted, and others where it will not be allowed or feasible due to system failures, highly complex traffic situations, human factors and possibly other reasons. At these areas, many AVs will have to perform ToCs. We refer to these areas as “Transition Areas” (TAs).

TransAID develops and demonstrates traffic management procedures and protocols to enable smooth coexistence of cooperative and automated vehicles (CAVs), AVs of different SAE (Society of Automotive Engineers) levels, cooperative vehicles (CVs) able to communicate via vehicle-to-everything (V2X), and legacy vehicles (LVs), especially at TAs. A hierarchical and centralized approach is adopted, where control actions are implemented at different layers including Traffic Management Centres (TMC), roadside infrastructure, and vehicles. Following this approach, in the TransAID project, different services have been defined addressing specific complex traffic situations at Transition Areas. The road infrastructure supports the coordination of manoeuvres of vehicles by providing advices, notifications or information to vehicles in order to increase the overall traffic safety and efficiency.

To validate the effectiveness of the traffic management measures developed at the TransAID project simulations taking into account traffic safety and efficiency metrics will be performed. For the simulations to be as reliable as possible, the most relevant microscopic traffic models for mixed traffic behaviour and interactions with Automated Driving (AD) cars are developed [3]. Also, communication protocols for the cooperation between CAVs, CVs, and Road Side Units (RSUs) are implemented, modelled and included. Based on the results of these simulations, the most promising solutions are then implemented as real-world prototypes and demonstrated in closed and controlled environments as proof of concepts for real world’s technical feasibility

1.2 The TransAID iterative approach

The hierarchical and centralized approach of the TransAID project is applied over two iterations, each taking half of the project’s total duration. During the first iteration, the focus is on studying aspects of transition of control and transition areas through basic scenarios. This implies that realistic models for AD and communication protocols need to be developed and/or adopted to cover the requirements of these scenarios’ simulations. Using the basic scenarios, it is possible to run initial simulations and focus in detail on the relatively new aspects of ToCs, TAs and measures mitigating negative effects of ToCs. The goal of the first iteration is hence to gain experience with all aspects relevant to TAs and mitigating measures. In the second iteration, the achieved experience

is used to improve/extend the traffic management measures while at the same time increasing the complexity of the investigated scenarios (e.g. including more challenging scenarios not considered in the first iteration, or combining multiple scenarios in the same evaluation). The second iteration will consequently need additional functionalities from the traffic and communication protocols point of view, whose modelling will be implemented at later stages.

1.3 Purpose of this document

The TransAID consortium has selected five services to be implemented in the first iteration of the project. These services define traffic management measures that require the use of communications between vehicles and between vehicles and the road infrastructure. In particular, the traffic management measures defined at the TransAID project employ communications for two main tasks: gathering information about the traffic stream through cooperative sensing and support in the coordination of the vehicles manoeuvres through cooperative manoeuvring.

In this document we elaborate on the cooperative sensing and driving aspects of the traffic management measures for the TransAID services selected in the first iteration of the project. On one hand, this document first describes the different type of sensors that can be available at the vehicle side and at the infrastructure side. It also presents novel mechanisms for the fusion of sensor information at the vehicle and at the infrastructure. TransAID services employ cooperative sensing (referred to as collective perception in ETSI (European Telecommunications Standards Institute)) to improve the vehicles' and infrastructure's perception of the driving environment through the exchange of sensor information. ETSI is currently defining the so called Collective Perception Service (CPS), and the current focus is on the definition of the appropriate generation rules of the Collective Perception Message (CPM). A comprehensive analysis of the effects of different generation rules in terms of communications and information awareness has been done in TransAID employing advanced communications simulation tools, and has been presented and discussed at ETSI meetings to contribute to the standardization process (see Annex A). On the other hand, this document also defines the first version of the message flows between vehicles, and between vehicles and the road infrastructure necessary to implement the cooperative driving manoeuvres specified in the traffic management measures of the different TransAID services. ETSI is also defining the so called Maneuver Coordination Service (MCS). The current concept proposed at ETSI has been extended in TransAID to include the support of the infrastructure in the coordination of the cooperative manoeuvres of vehicles. The TransAID proposal for the MCS has also been presented and discussed at ETSI meetings to contribute to the standardization process (see Annex A). Furthermore, a preliminary analysis of the effects of different types of V2X message generation rules for the MCM (Maneuver Coordination Message) has been done as an exploratory study that will guide our work of the second iteration in this area.

The definition of the cooperative sensing and driving mechanisms presented in this document are based on the V2X Facilities layer message set defined in Deliverable 5.1 [4]. The work conducted has also taken into account the traffic management measures defined in WP4 (see Deliverable 4.2 [5]) and the cooperative manoeuvres modelled in WP3 (see Deliverable 3.3 [6]). Following the iterative approach of the TransAID project, these definitions will be redefined in the second version of this deliverable to be presented in M30 of the project. The revised version will take into account the new version of the V2X Facilities layer message set defined in WP5, the new traffic management measures defined for the new services selected in the second iteration of the TransAID project and the results of the real-world implementation done in the first iteration of WP7.

1.4 Structure of this document

This document is divided into two main blocks aligned with the two tasks (task 5.2 and task 5.3 of WP5) that directly contributed to the developments described here. The outputs of task 5.2 are presented in Section 2 while the outputs from task 5.3 are shown in Section 3.

Section 2.1 describes the state of the art of cooperative sensing including information about the type of sensors employed at vehicles and at the infrastructure and the review of the current status of the standardization of the CPS. Section 2.2 present novel cooperative sensing mechanisms that enhance the overall environmental perception. Section 2.3 presents a comprehensive analysis of the CPM generation rules that take into account the improvement of the CPM in terms of information awareness and also the feasibility of the transmission of CPMs in terms of communications.

Similarly, Section 3.1 describes the state of the art of cooperative driving, the current status of the standardization of the MCS and the TransAID proposal for the MCS. Section 3.2 describes the message flow needed to execute the traffic management measures of the TransAID services. Section 3.3 describes the message flow needed for the execution of a cooperative lane change following the TransAID approach for the MCS. A preliminary analysis of the MCM generation rules in terms of the channel load is presented in Section 3.4.

Finally, Section 4 briefly concludes the deliverable summarizing the results and providing some considerations on the future work to be done in WP5 during the second iteration of the project.

1.5 Glossary

Abbreviation/Term	Definition
AD	Automated Driving
AID	Automatic Incident Detection
AoI	Area-of-Interest
AV	Automated Vehicles
CAM	Cooperative Awareness Message
CAS	Cooperative Awareness Service
CAV	Cooperative and Automated Vehicle
CBR	Channel Busy Ratio
C-ITS	Cooperative Intelligent Transport Systems
CoG	Centre of Gravity
CPM	Collective Perception Message
CPS	Collective Perception Service
CSM	Cooperative Sensing Message

CV	Cooperative Vehicle
DCC	Decentralized Congestion Control
DE	Data Element
DENM	Decentralised Environmental Notification Message
DF	Data Field
DX.X	Deliverable X.X
EPM	Extended Perceived Message
ETSI	European Telecommunications Standards Institute
FoV	Field-of-View
GNSS	Global Navigation Satellite System
HMI	Human Machine Interface
INS	Inertial Navigation System
ITS	Intelligent Transport System
ITS-G5	Access technology to be used in frequency bands dedicated for European ITS
ITS-S	ITS station
LV	Legacy Vehicle
MC	Management Container
MCM	Manoeuvre Coordination Message
MCS	Manoeuvre Coordination Service
MRM	Minimum Risk Manoeuvre
MTU	Maximum Transfer Unit
ORC	Originating RSU Container
OSC	Originator Station Container
OVC	Originator Vehicle Container
PDF	Probability Density Function
PDR	Packet Delivery Ratio

PER	Packet Error Rate
POC	Perceived Object Container
PSR	Packet Sensing Ratio
RoI	Region-of-Interest
RSU	Road Side Unit
SAE	Society of Automotive Engineers
SDC	Station Data Container
SIC	Sensor Information Container
SLAM	Simultaneous Localization And Mapping
SUMO	Simulation of Urban MObility
TA	Transition area
TMA	Traffic Monitoring Area
TMC	Traffic Management Centre
ToC	Transition of Control
ToR	Take-over Request
TransAID	Transition Areas for Infrastructure-Assisted Driving
V2I	Vehicle-to-infrastructure
V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-Everything
WP	Work Package

2 Cooperative Sensing

Automated vehicles are equipped with multiple exteroceptive sensors (e.g. LIDARs, RADARs, sonars and cameras) to perceive their local environment, and thereby perform control operations and execute Intelligent Transport System (ITS) services. This local perception information makes the AVs aware of objects (e.g. other vehicles, trees, cyclist, roadside rocks, etc.) that are present in the driving environment. However, the perception capabilities of each sensor are limited to a certain detection range and a given Field-of-View (FoV). In addition, these capabilities can be impaired due to the presence of obstacles (obstructions) in the field of view, sensors blind spots, adverse weather conditions and sensitivity to ambient light and temperature, among others. These limitations can significantly degrade the perception capabilities of AVs, and hence negatively influence their safety and driving efficiency. For example, it could limit the demands of the AV systems to detect objects present in its Region-of-Interest (RoI) or Area-of-Interest (AoI). [7] and [8] define this AoI/RoI to be equal to 300 meters for performing safety applications in AVs. This range is hard to achieve with the current exteroceptive sensors FoV.

CAVs can improve their perception capabilities thanks to the exchange of sensor information using wireless technologies such as IEEE 802.11p/ITS-G5 [9] or C-V2X/LTE-V [10]. This is generally referred to as collective perception or cooperative sensing. Collective perception enables CAVs to improve their perception of the surrounding environment by receiving from other vehicles and/or infrastructure nodes information about objects that are beyond their sensing range. It can also improve CAVs' detection accuracy and increase the confidence about the detected objects. Collective perception can also help mitigate the negative impact of adverse weather conditions on the sensing capabilities as well as the initial limited CAV market penetration rate. The collective perception concept can also be extended to infrastructure nodes with ITS sensing capabilities. These nodes can transmit and receive sensor information to/from vehicles to improve their respective knowledge of the driving environment. Collective perception enables the exchange of sensor information to improve their perception of the driving environment. It enables vehicles (and the infrastructure) to detect objects, e.g. non-connected vehicles, pedestrians, cyclist, obstacles, etc., beyond their local sensing capabilities. By improving the vehicles' perception of the driving environment through the exchange of sensor information, collective perception seeks improving the safety and traffic efficiency of connected and automated vehicles.

In general, the cooperative sensing or collective perception process has shown to include and rely on a set of functionalities that are illustrated in Figure 1. First, the cooperative sensing benefits from the sensors (vision, LIDAR, RADAR, sonar), and the data they provide, that AVs utilize to perform automated operations and to manage the necessary control operations. In the collective perception process, this data is enriched (new data/objects, and increased accuracy and confidence about the detected data/objects) when it is fused with sensor data received from neighbouring CAVs/infrastructure. Then, the 'detection & fusion' function processes and fuses the data acquired by the in-built sensors. This function aims at identifying objects by analysing features like edges, regions and attributes, and saving them in a local database. The 'message generation' takes the locally stored perception information to form the collective perception messages (this could include fused information or sensor specific object data). It should be noted that the information included in the collective perception messages could be of any nature: raw sensor data [11] (this is not practical though), or processed objects with a specific description format [12]. The nature of the data to be transmitted can be decided based on existing trade-offs between the data size, processing cost and resolution/accuracy. Another important aspect of the 'message generation' function is to decide when vehicles should exchange the collective perception messages. This decision is made considering the defined generation rules, as indicated above. Finally, the 'congestion control' function acts as a gatekeeper before the messages are transmitted through the radio unit. In

particular, the ‘congestion control’ function is designed to avoid the saturation/congestion of the communications channel. To this aim, the ‘congestion control’ function can perform rate, flow and/or power control strategies to maintain the channel congestion level at a certain level (or below a defined threshold).

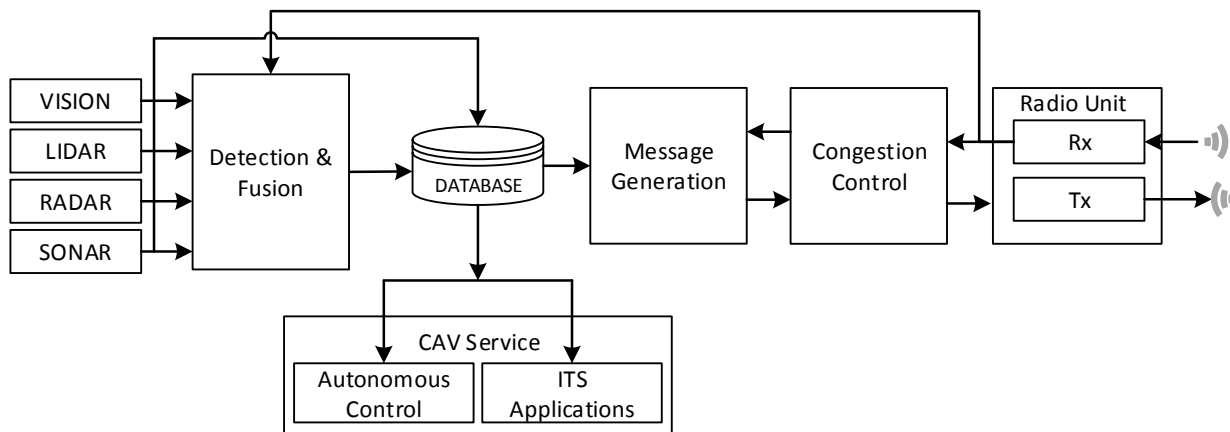


Figure 1. Collective Perception Functionalities.

The ETSI Technical Committee on ITS is currently developing the European standards for collective perception or cooperative sensing. They are defining a new module at the Facilities layer referred to as collective perception service to enable the exchange of sensor information about the status and dynamics of detected objects. The standardization process will define which information should be exchanged about the detected objects, and how often it should be exchanged. In particular, ETSI is currently designing the V2X message (known as Collective Perception Message) necessary for vehicles to exchange sensor information about the status and dynamics of detected objects. Another important aspect yet to be decided is the CPM generation rules that define when vehicles should exchange CPM messages. These generation rules will have a significant impact on the effectiveness of the collective perception service and on the wireless vehicular network. In fact, if vehicles exchange information about detected objects very frequently, they will significantly improve their perception capabilities and be able to detect their surrounding objects with higher accuracy. However, a too frequent exchange of CPM messages can also saturate the communications channel to the point that these messages cannot be transmitted, ultimately reducing the effectiveness of the collective perception service.

The rest of this section is organized as follows. Section 2.1 presents the current state-of-the-art on cooperative sensing. Given the importance of the sensors for the collective perception process, section 2.1.1 first reviews the type of sensors that are currently available in the CAVs and the infrastructure, and existing techniques to fuse the data these sensors generate. Section 2.1.2 then summarizes existing studies on collective perception conducted to date. This includes an analysis of the current efforts on the ETSI standardization of the CPS, the CPM message, and generation rules. Sections 2.2 and 2.3 then show the main contributions of TransAID to progress the current state of the art. In particular, Section 2.2 presents the techniques and models developed under TransAID to enable the sensor data fusion at the infrastructure and vehicles. Finally, Section 2.3 analyses, under different driving conditions, the performance and efficiency of different CPM message generation rules that are currently discussed at ETSI. This analysis has been presented at ETSI to contribute to the standardization process (see Annex A).

2.1 State of the art

2.1.1 Sensor information

CAVs require a comprehensive model of the environment for safe automated operation. In a collective perception environment this model is generated from sensors mounted not only on the ego-vehicle itself but also from data acquired by other CAVs as well as other CVs and road infrastructure. CPM defines a V2X message for the exchange of such information in the form of an abstract description. This description must be generated from the raw sensor data in a pipeline of sensor-specific processing steps and, at the receiving end, the world model must be enriched with the abstract description of other ITSs. Fusion of different sensor sources must happen under consideration of involved sensor uncertainties in order to generate a fused environment model with increased accuracy compared to the single sensor model. This section reviews existing and upcoming sensor configurations with regard to the information exchange via CPM in TransAID. In addition to that, cooperative traffic will be investigated, e.g. by using CAM messages [14] and others if available.

2.1.1.1 In-vehicle sensors

2.1.1.1.1 Environment sensing and ego-localization

Considered are exteroceptive sensors which gather information about the environment at some range. Typical sensors and their possibilities by state-of-the art processing techniques are:

- Monocular camera: image and video, image differences, angular information of tracked objects, possible full 3D info when projection to ground is possible,
- Stereo camera: as monocular camera, plus range information through depth images. Range depending on camera distance, typically 2-30m at 30cm baseline,
- Active cameras (Time of Flight / Photo mixer device): typically camera with rather low pixel resolution, plus near range depth (<10m),
- SONAR: distance of object (usually without identifying it) within field of view, range typically 0-3m,
- RADAR: distance of object, typically including identification. can be high-range (200m+) depending on sensor,
- LIDAR: rather high-resolution 3D point cloud from measured object distances, including object identification and tracking, various range types from 30m to 200m possible. various types of fields of view (e.g. single distance spot, single line scanning, multiple line scanning, 360° rotating FOV).

Together with environment sensing, ego-location, velocity (linear and angular) and timing will be required in most use cases. Position and timing are typically available through Global Navigation Satellite System (GNSS), plus optional inertial navigation systems (INS). Sources like map matching, wheel odometry or environment sensor-based techniques (landmark navigation, Simultaneous Localization And Mapping (SLAM), visual odometry) can be an extension alternative to GNSS positioning. Such techniques are important on GNSS position dropouts (e.g. signal interruption, multi-path, jamming) and when relative navigation (e.g. within legacy traffic flow, narrow track guidance) is required. For a typical GNSS/INS, the outputs are:

- 3D geodetic position (e.g. WGS84 or UTM plus ellipsoidal or geoid height), optional RTK with improved accuracy augmentation (SBAS, GBAS, DGNSS),
- 3D velocity estimate,
- precise time,
- heading estimate on multi-antenna receivers,

- 3D attitude and high-frequent position and velocity updates when using GNSS/INS strapdown,
- 3D acceleration and turn rates with INS,
- uncertainty estimates by GNSS DOP and filter covariance.

Depending on the application context, state information is often reduced (e.g. only 2D position and heading for ground transportation, plus their derivatives) and can also be locally centred (e.g. Cartesian position relative to lanes or other infrastructure).

2.1.1.1.2 Example Configuration

On the vehicles, GNSS navigation and environmental object data (at most from image, RADAR or LIDAR-based identification and tracking) is taken into account. This will generally provide two message types:

- Cooperative Awareness Message (CAM) (generated from GNSS or GNSS/INS and static vehicle parameters),
- Collective Perception Message (generated from object data from at least one environmental sensor linked to GNSS/INS).

Testing configurations are described in D7.1 [13]. The configuration is generally based on DLR's vehicle availability and installed hardware – currently this comprises multiple and co-calibrated LIDARs (currently three at front and one at rear) with altogether almost 360° FOV (except some gaps at the vehicle sides). Optionally, one front RADAR, and cameras can be taken into account if advantageous. Navigation and timing data are obtained by a NovAtel GPS/INS solution. Depending on the testing area, precise RTK which uses self-operated DGPS or SAPOS can be used.

2.1.1.2 Infrastructure-mounted sensors

2.1.1.2.1 Inductive loop

The default sensor for infrastructure-based detection is the inductive loop. The detection principle is based on the increase of inductance of a coil when a metal core is added, the magnetic field lines are shown in the sketch below:

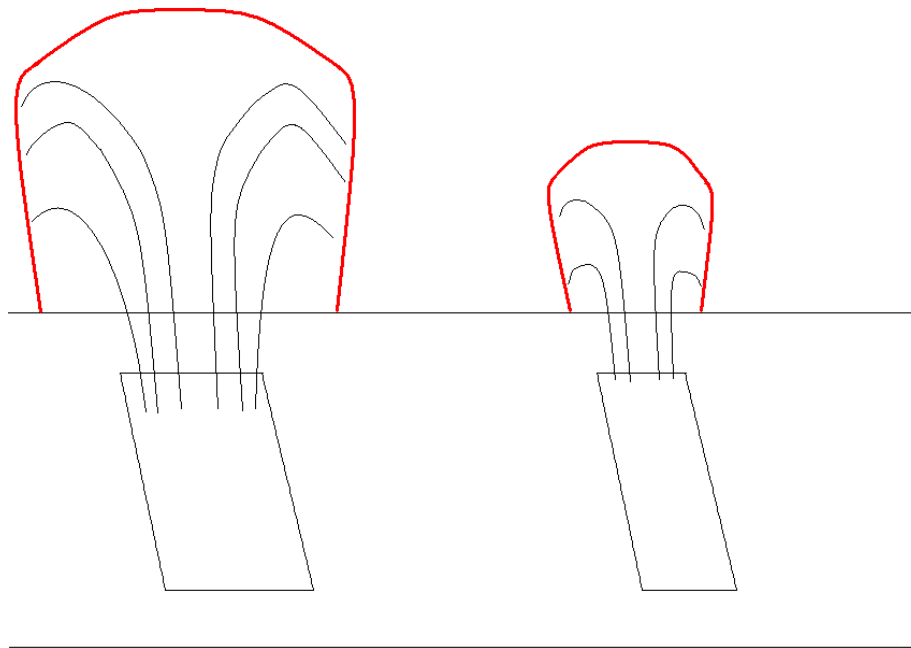


Figure 2. Magnetic field around inductive loop.

As can be seen a smaller loop has a smaller reach of the field lines and will therefore behave differently when a vehicle with a high ground clearance passes over it. While smaller loops are more precise in detecting vehicles at a particular location, making the loop too small may result in problems detecting trucks and agricultural vehicles. For motorway systems the default size of a loop is 1.5m x 1.8m (1.5 is the length in the driving direction), while urban systems use 1.0m x 2.0m, but it should be noted there is a high variety for urban systems in loop design, where even parallelogram shapes are often used.

In the figure below the amplitude of the relative inductance change over time is shown for a common private car (Volvo V40 early 2000 model), this pattern is referred to as the “vehicle signature”:

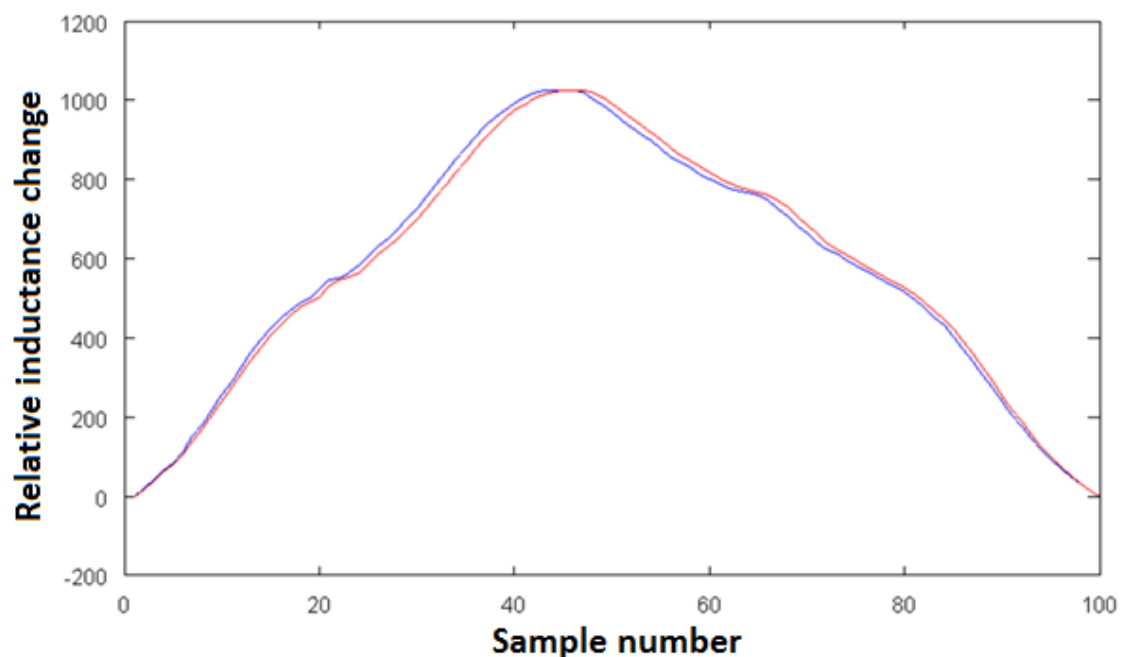


Figure 3. Vehicle signature generated by passing over an inductive loop.

The data was captured on a double loop while the vehicle was accelerating; the first vehicle signature is indicated by the blue graph, the second by the red. The detector card was set to sample the relative inductance change every 3ms, resulting in 100 samples of the vehicle passage that could be considered above noise level.

The double loop is an interesting case because vehicle speed can be measured instead of estimated based on an assumption of the vehicle length. The duration of the loop output being over a certain value, i.e. the signature length, depends on both the vehicle length and the speed, so for a single loop this has to be estimated as both variables are unknown. In order to measure the speed on a double loop, the time difference for a reference point in the signature is used. Common references are Centre of Gravity (CoG), rising/falling flank and peak value.

While presence detection is easy with a close to 100% accuracy given proper loop placement and dimensions, the speed has some inaccuracy due to noise and deformation of the signature. Therefore, this accuracy is 97% or higher for Dynniq hardware (certified by the Dutch authority called “Nederlands Meetinstituut”). Cyclists and motorcycles have a very low metal content, especially with upcoming carbon technologies, and can sometimes be missed by detectors.

Theoretically, it would also be possible to measure the acceleration of a vehicle by comparing the deformation of the signatures or analysing the difference in travel time between the rising and falling flank. This has not yet been integrated in existing hardware due to low market demand for such a feature.

2.1.1.2.2 RADAR and video sensors

Due to inductive loops being the standard solution, both video and RADAR detectors follow the same principle and draw a virtual loop inside the field of view for detections.

In case a vehicle is inside the area of a loop, the infrastructure gets the signal “occupied” just like for the real induction loop. Problems arise with extreme weather and small errors can be made when birds pass in front of the camera. Sensor occlusion is a problem for any sensor that does not observe the traffic on a perpendicular angle to the road surface; this happens mostly for detection of private cars behind tall trucks. Calibration and positioning of the sensor are therefore very important to minimize this.

In general, infrared is less sensitive for extreme weather conditions and has the best performance for cyclist detection. Visible light is the cheapest technology but suffers from extreme weather, sun glare and is more difficult to filter for specific vehicle classes. RADAR is more accurate with moving objects while cameras are more accurate for stopped objects. Therefore, the *TrafiRADAR* is a promising new sensor that combines RADAR with visible light detection to track vehicles on a stretch of road determining their position and speed.

According to factory specifications these sensors all have a very high accuracy >98%, which is measured under ideal circumstances and can be disappointing in real-world scenario's. Therefore, it is recommended to search for independent evaluations or practitioners experience before deployment.

2.1.1.2.3 Example configuration

As the vehicle configurations, the testing RSU camera setup is described in D7.1 [13]. Bases are off-the-shelf surveillance cameras to be mounted with FOV towards the testing area, together with networking and V2X hardware.

Dutch motorways generally have an inductive loop pair installed every 600-1000 meter in conjunction with a gantry with panels that warn drivers for traffic jams. This is part of a so-called Automatic Incident Detection (AID) system. The distance between the gantries varies depending on

the location of curves, bridges and viaducts, because there should always be line of sight with one set of panels for traffic. Without specific conditions, the distance is 800 meter.

In urban areas there are several types of loops installed. The most common is the stop line detector, it detects whether a vehicle is waiting for a specific signal. If this is not the case, the signal can be skipped for dynamic controllers. Once a traffic light is green, it can also be used to detect when the queue has cleared and the light can switch to amber and red again. However, this is not very efficient because a margin of approximately 2 seconds is required to be certain there is no vehicle that accelerated a bit slower left behind. This means that the light switches to amber 2 seconds after the last vehicle left the queue. More efficient is to put a large detector a bit further upstream. Typically, these detectors have a length of 20-40 meter in the driving direction and are placed 20m upstream. The large length means that there is no time margin required anymore to cover the gaps between vehicles. Placing it a bit upstream means that as soon as the last vehicle leaves the loop, the light can switch to amber, while the vehicle is so close that it won't stop anymore. Effectively, the green phase can be 3-5 seconds shorter with such detectors. More advanced controllers that model the vehicles approaching the intersection also require upstream entry detection. These are again smaller loops of 1 meter in the driving direction to enable counting. In networks, the entry detection is effectively an exit detection of an upstream intersection.

2.1.1.3 Sensor fusion

Automated vehicles are typically equipped with a variety of sensors, which each have different properties in respect to reliability in different weather conditions, accuracy and precision, viewing range and resolution (see D7.1 [13]). Sensor fusion algorithms are used to combine measurements from different sensor sources in a way that the combined output is of higher quality than the output of each individual source. Therefore, a good sensor fusion algorithm levels out weaknesses of the individual sensors based on a-priori knowledge about the involved sensors and physical constraints that allow assessing if an object hypothesis is found or not, for example based on known object motion models and calibration parameters. The mathematical framework behind most sensor fusion algorithms applies probabilistic reasoning on the uncertainty of individual sensors and object motion models, for example using Kalman filtering or Bayesian networks [15].

The sensor data that is shared between ITS stations (ITS-Ss) in a collaborative perception environment can be regarded as additional sensor sources that (a) increase the field of view of individual ITS-S and (b) reduce the uncertainty associated to individual object hypotheses. As such, the shared information can be incorporated into the environment perception as part of the sensor fusion architecture similar to sensors which are directly connected to the ITS-S in hardware. The remainder of this section summarizes different sensor fusion architectures and reviews possibilities for the integration of collaborative perception data via CPM.

2.1.1.3.1 Sensor fusion architectures

Existing sensor fusion architectures can be categorized according to the level in the processing chain where the sensor data is combined:

Low-level fusion: In low-level fusion, the raw sensor data is combined into a common representation on which subsequent processing steps operate. For example, sensor data of multiple LIDAR can be combined into a common point cloud of increased angular resolution and vertical field of view (see Figure 4). Another common low-level fusion strategy is based on occupancy grid maps. The occupancy grid map (see Figure 5) is a discrete representation of the environment in which each cell contains the probability that a region in space is occupied by an obstacle. This probability can be computed based on the output of multiple sensors and sensor modalities [16].

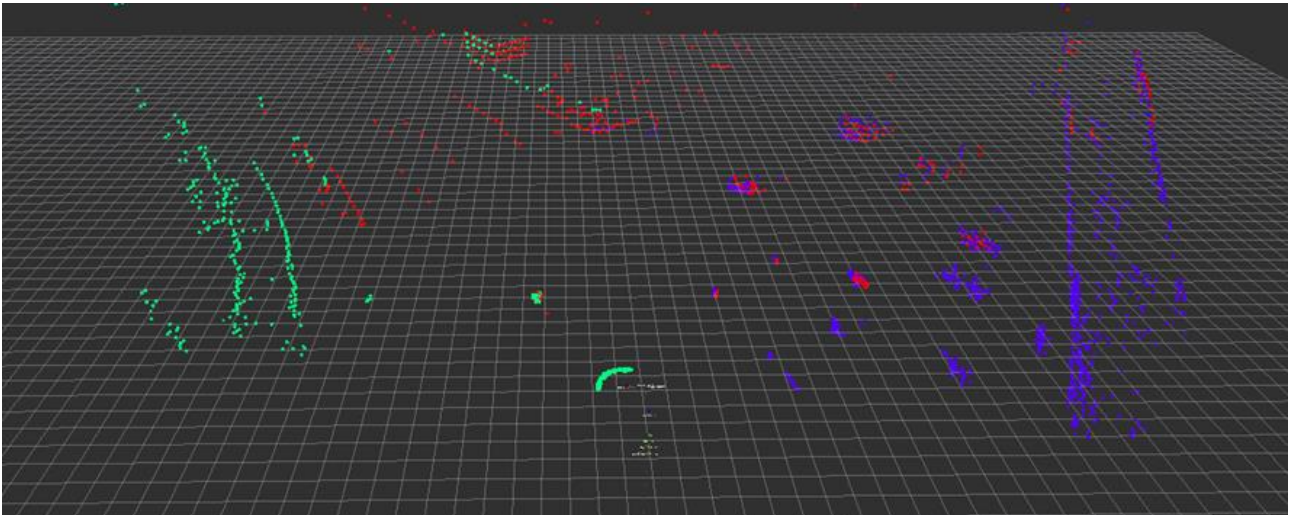


Figure 4. The sensor returns of three Ibeo LUX LIDAR (shown in green, red and blue) are registered into a common point cloud to increase vertical field of view and angular resolution. Further processing steps operate directly on the combined point cloud.

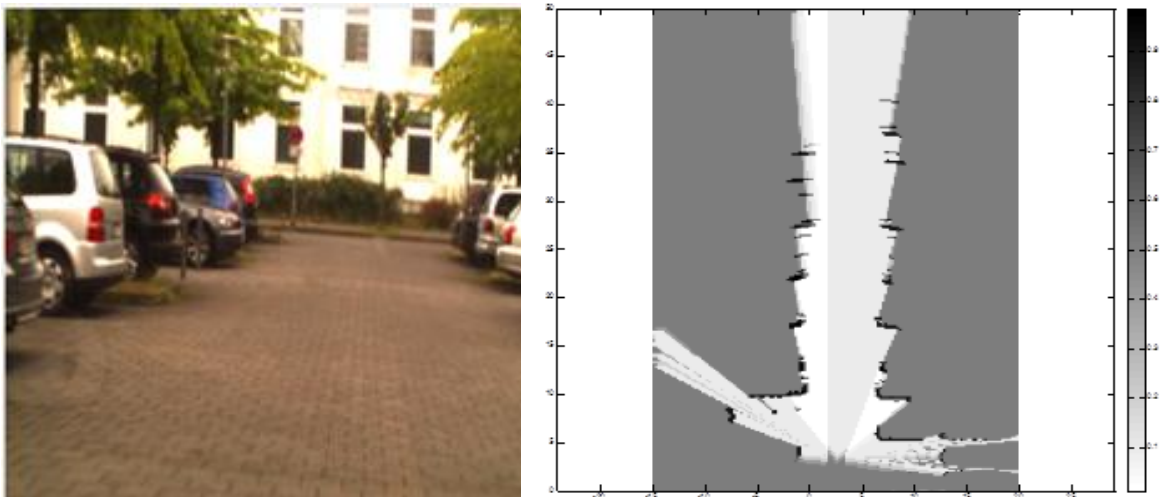


Figure 5. Left: camera image, right: corresponding occupancy grid map generated from LIDAR data.

Detection-level fusion: In detection level fusion, the raw sensor data is pre-processed to obtain detection responses from each of the available sensors, e.g. by thresholding the intensity of the returned signals. Then, the fusion algorithm combines these detections into a common representation. Two sources of uncertainty must be dealt with in detection-level fusion: sensor noise and unknown data association. Handling of sensor noise can often be solved optimally or nearly optimal in a recursive Bayesian filtering formulation using Kalman, particle or histogram filters [17]. Data association on the other hand is a much more challenging problem due to the combinatorial nature of the problem: if the identities of the objects which have generated the observed detections are unknown, the number of possible object trajectories grows exponentially with the number of detections and time steps. This makes multi-object (and multi-sensor) tracking an NP-hard problem.

Yet, principled approaches exist. For example, multiple hypothesis tracking enumerates all possible object trajectories and applies pruning strategies based on their likelihood in order to only follow the most probable hypotheses [18]. More recently, methods based on random finite sets [19],[20]

have become popular. These methods follow a rigorous mathematical treatment of recursive Bayesian filtering of set-valued phenomena.

Track-level fusion: In track-level fusion each sensor has its own processing pipeline to generate object hypotheses from raw sensor data. The generated tracks are then combined into a global representation using matching algorithms. Thus, compared to the detection-level fusion, in track-level fusion the matching is done at trajectory level [21]. An example of a track-level fusion architecture is shown in Figure 6.

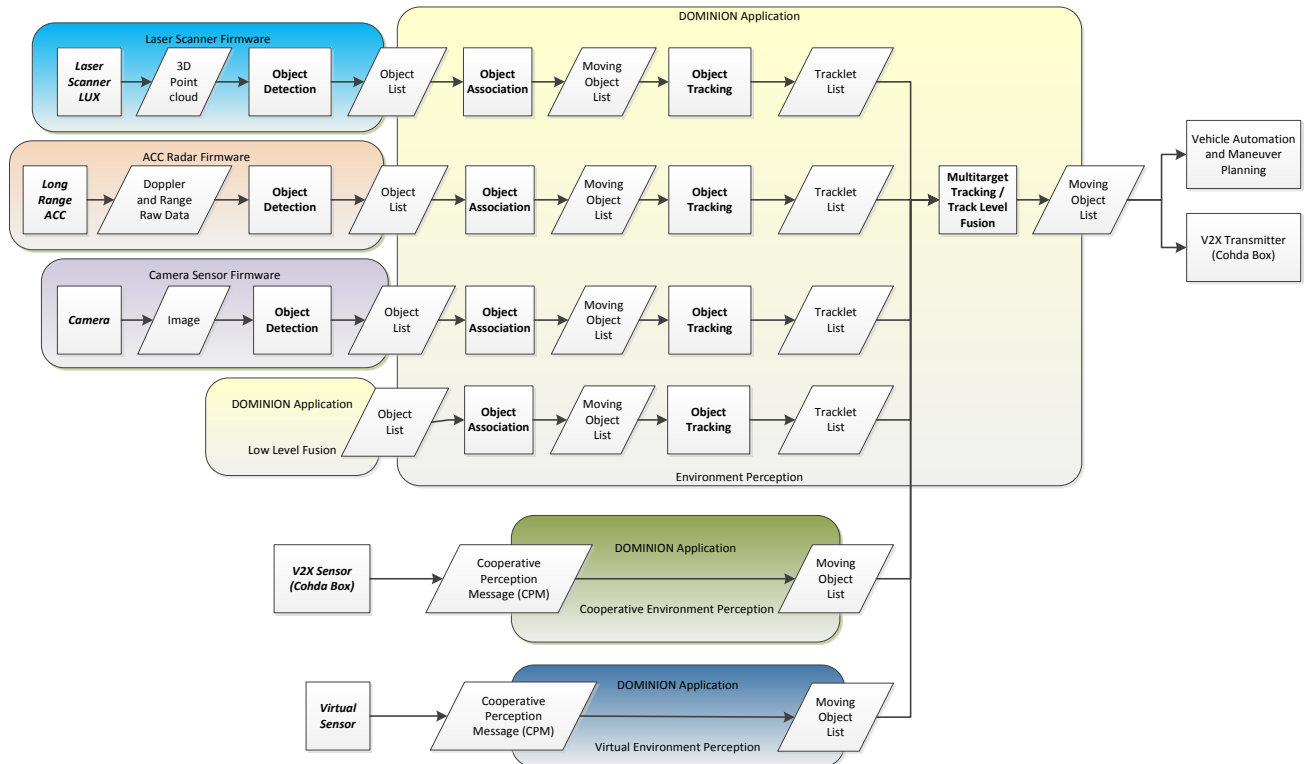


Figure 6. Track-level fusion building blocks. Each Sensor applies its own processing chain. The track-level fusion aggregates these object hypotheses into a common representation [22].

Generally, the less aggregated the data to be fused the bigger is the potential of data quality improvement by a good data fusion technique. The reason is that the later the stage, the higher is the level of data aggregation and the more data is lost before fusion. Further, compared to lower-level fusion, track-level fusion algorithms typically cannot provide guarantees such as Bayes optimality. However, depending on the application scenario, track-level fusion schemes may be advantageous over lower-level fusion because individual sensors operate separately, thus reducing the computational load at the fusion centre as well as the communication bandwidth.

2.1.1.3.2 Integration of CPMs into fusion architecture

The CPM definition imposes no requirements on real-time capabilities of the network transmission. Thus, messages may be received with a significant delay or even out-of-order. Further, the CPM contains processed sensor data on a per-sensor basis. As consequence, the data shared via CPM can only be integrated at the detection-level or track-level. A detection/track-level fusion scheme is therefore the most feasible approach.

Independent of the concrete system architecture, fusion systems typically apply probabilistic reasoning. In this regard, the CPM definition contains all relevant sources of uncertainties. Both, sensor and reference position and orientation are contained in the message definition. Based on this

information, sensor output of one ITS-S can be incorporated into the system state of other ITS-Ss. Both fields have an uncertainty attached to them in form of a 95% error quantile with respect to the ITS-S coordinate system. Depending on actual sensor characteristics, these quantiles may represent a significant simplification compared to the true uncertainty representation. The 95% error quantile characterises a covariance matrix with only diagonal entries, thus capturing the variance along the coordinate axes of the reference system. If the actual sensor coordinate system is misaligned in rotation, the covariance in the reference system likely contains off-diagonal entries. . Covariance is calculated by sensor measurement uncertainties (e.g. pixel, distance, or stereo triangulation uncertainty) plus systematic errors due to extrinsic sensor misalignment. For cameras with large uncertainty in depth this may cause crude approximations.

Some sensors may not be able to measure all the fields in the CPM definition directly, in particular velocities and accelerations. While it is often possible to estimate corresponding values through Bayesian filtering, this must not hold for all sensor configurations. If “unknown” values are not allowed (as e.g. some parameters within the CPM are optional), such a case could be handled by setting the associated uncertainty to infinity or a numerical approximation.

Care should be taken with respect to which data is sent out by individual ITS-S. In order to prevent sensor data to be integrated multiple times into the fusion algorithm (this would lead to underestimated covariances), the sent data should not include information which was previously received from another ITS-S. Therefore, each ITS-S may only send the object hypotheses of its individual sensors, not the fused system representation that includes information from other ITS-Ss.

2.1.1.3.3 Sensor fusion at inductive loop infrastructure

Low-level fusion takes place at this type of infrastructure as well. As described in section 2.1.1.2.1 the inductive loop detectors analyse the vehicle signatures in more detail to draw conclusion about presence (profile value above threshold) and speed (comparing time difference of reference point on double loop).

More interesting is the fusion between different sensors, these can even be sensors of the same type. On intersections with an adaptive control algorithm there is usually a “queue model” that models the arrivals upstream of the intersection towards the stopline and heuristics with loops on the stopline to conclude a vehicle has passed the stopline. The most challenging aspect is the estimation of the turning ratio's, since upstream only a guess can be made whether the vehicle is turning right, straight or left. This means stopline detectors have to be monitored continuously to conclude which direction vehicles are going. An example of a queue model is shown in the figure below:

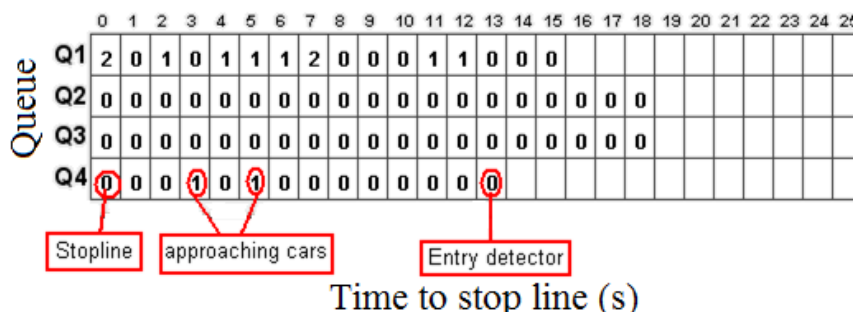


Figure 7. Example of shift-register as queue model.

Vehicles enter the model when they pass the entry detector and every second they are shifted one cell to the left, representing getting one second closer to arriving at the stopline. The leftmost cell represents the amount of vehicles waiting at the stop line. Once a vehicle passes the stop line, generally during a green phase, one vehicle is subtracted from this cell.

When two different sensor technologies are combined or C-ITS (Cooperative-ITS) messages are received, a different kind of fusion technique is required. For example, when a vehicle transmits a CAM message from which it can be concluded it is at a distance of 4 seconds to the stop line in Q4 in Figure 7, a fusion algorithm has to decide which vehicle in the queue model matches the CAM data. When a CAM is also sent with car following distance (see CAM extensions of the TransAID project at Deliverable 5.1 [4]), this will be easier, as there is no vehicle ahead of the vehicle in cell 3, while there is one vehicle ahead of the one in cell 5. In the TransAID project these fusion algorithms had to be designed and implemented, especially for the motorway merging service, which requires accurate data of the approaching traffic. This is further described in 0.

2.1.2 Existing studies on collective perception

Different studies have explored the potential of sharing sensor information for collective perception. For example, [23] and [24] were some of the first studies focused on analysing different sensing and fusion techniques. In these two studies, the raw sensed information was directly exchanged between vehicles. Alternatively, Kim *et al.* [11] investigated the exchange of raw sensor data, processed metadata (e.g. lane information represented in the point cloud) and compressed data (e.g. images from camera sensor) for collective perception. The results show that the communication delay increases with the amount of data transmitted so unnecessary data should be avoided.

To minimize the bandwidth required for collective perception and reduce the latency, [25] investigated the concept of sharing detected object data instead of raw sensor data. In this study, authors experimentally evaluate through field tests the transmission latency and range for different message sizes and rates. In addition, the study proposes a fusion architecture that includes a local fusion function (to process the ego-vehicle sensor data) and global fusion function (to process the object data from different ITS stations) aimed at minimizing the amount of information to share.

Günther *et al.* [12] extended the message concept proposed in [25] for collective perception with different containers in order to specify the detected object parameters, sensor configurations and the characteristics of the transmitting vehicle. This information is used by the receiving vehicle to perform the coordinate transformation and locate the detected objects. The efficiency of the proposed message is investigated with an obstacle avoidance scenario with two vehicles. The results show that the proposed solution allows vehicles to detect earlier a possible obstruction and hence improves the reaction time to handle a potential safety risk. The collective perception message concept proposed in [12] was evaluated under different low traffic densities in [26] and high traffic densities in [27]. Both studies considered different priority queues and Decentralized Congestion Control (DCC) mechanisms [28] with five different level of congestion states. Each state holds a specific packet transmission interval and the state transition is performed based on the measured Congestion Busy Ratio (CBR). In addition, two message variants were configured to share the collected perception information among V2X enabled vehicles. The first variant includes CAM and EPM (Extended Perceived Message) that are transmitted pairwise, and the second variant extends the CAM message by adding collective perception related data fields. These studies analyse the awareness ratio and channel load for scenarios with different CAVs market penetration rates. From the results, the authors conclude that the collective perception or cooperative sensing increases the awareness of the driving environment but could also increase the network congestion. Suggestions were made by the authors to incorporate collective perception information in the existing CAM [14] (an extended version) or move collective perception messages from the control channel (where CAM messages are transmitted) to a service channel [29].

Recently, the AutoNET2030 project [30] has developed a cooperative autonomous driving technology based on a decentralised decision-making system and incorporated cooperative perception as one amongst its major services to increase the perception range in the neighbouring

cooperative vehicles. The project implements the cooperative perception primarily to focus on the lane change scenario to vigilantly handle the blind spots of the vehicles. For this purpose, the objects perceived over the vehicle sensors are transformed into an occupancy grid data using an occupancy grid algorithm and exchanged with the neighbouring vehicles. As the size of the occupancy grid data can rapidly grow based on the cell size, grid size and bits per cell, the exchanging content might exceed the packet's Maximum Transfer Unit (MTU) specified by the ETSI ITS-G5 standards. Hence, a real-time encoding and decoding algorithm is applied to the occupancy grid data to fit the information in one packet. AutoNET2030 proposes to exchange the occupancy grid data among ITS stations through a new message named Cooperative Sensing Message (CSM); the CSM is actually derived from extending the standard CAM message. AutoNET2030 also proposes to broadcast the CSM messages on a service channel to reduce the channel load of the control channel.

Fanaei *et al.* studied in [31] a transmission rate control mechanism for the collective perception and proposed an adaptive communication scheme for cooperative automated vehicles that dynamically controls the size/length and content of the messages based on the communication channel load. In the proposed system, the vehicles share a multi-resolution local map which is derived from three distinctive sources that include the local sensing modalities, previous environmental knowledge and processing map data. While the local sensing modalities and the previous environmental knowledge are obtained from the vehicle itself, the latter is procured from the neighbourhood vehicles. To have a reliable communication and to reduce the channel load, the proposed system adapts the size and content of the messages. On the one hand, the system adapts the size of the messages taking into account the CBR. On the other hand, the system adapts the content of the messages by identifying the potential known and the unknown objects that can be included in the message. Also, the system follows a hierarchical structure that includes all the potential unknown objects at the lowest resolution. Then the messages are filled by the inclusion of potential known objects. If any remaining space exists in the message, the resolution of the potential unknown objects is increased. The simulation-based study conducted in [31] shows that the proposed system is able to keep the Packet Error Rate (PER) below a defined threshold even with different densities of vehicles in the scenario. Gani *et al.* [32] extend the work presented in [31] and analyse the advantages of jointly controlling the transmission rate and length of cooperative sensing messages rather than controlling them separately.

The studies discussed so far focus mainly on V2V (Vehicle to Vehicle) communications. In [33], Wang *et al.* investigate collaborative sensing amongst vehicles assisted by the infrastructure and V2I (Vehicle to Infrastructure). In particular, [33] studies the possibility to utilize V2I to help relay data when V2V (based on mmWave) line-of-sight is not available. The obtained results show that V2I communications should be incorporated to support collective perception, especially at lower penetration rates of connected vehicles.

2.1.2.1 ETSI Collective Perception Service

ETSI TC ITS WG1 is currently working on the standardization of the Collective Perception Service (CPS) through the work items DTS/ITS-00167 and DTR/ITS-00183. The current developments are described in the Technical Report in [34] that will serve as a baseline for the specification of CPS in ETSI TS 103 324. The document reports the CPM format and its Data Elements, and the current CPM generation rules. In addition, the document discusses the use of message fragmentation and segmentation for large CPM messages, and the need to utilize multiple channels to avoid saturating the control channel. As the ETSI CPS standardization process is still ongoing, this section depicts the main ideas that are being outlined in the CPS drafting sessions and what to expect. However, all the information provided in this document regarding the ETSI CPS is preliminary and might be subject to alteration in the final version of the Technical Report.

2.1.2.1.1 Data Format Specification

The selection of a data format is essential to achieve reliability and efficiency in the CPS. Sharing raw sensor information is a simpler and straightforward approach but can create compatibility problems when shared among different technology or vendor providers. In addition, sharing raw sensor data consumes much higher channel bandwidth due to the large data size. To address these issues, the ETSI's CPS considers sharing the sensed information in a common/standard format using abstract (enumerated) object descriptions. The object description also includes information about the object dynamic state, geometric dimensions and time references. This common/standard format seeks eliminating compatibility issues. It also enables the classification of objects and the establishment of priorities and therefore the possibility to filter out objects that are redundant or unnecessary.

A key process to enable the object identification and classification is the feature extraction (e.g. edge detection). However, the mechanisms and technology involved in the sensor data's feature extraction is not discussed in the Technical Report, as it is considered beyond the scope of ETSI's CPS standard. Another important aspect of the format specification is the decision on whether to share individual objects detected by each sensor or to fuse the sensor data and share common objects at once. The former will avoid further processing delays, but it will incur a higher channel utilization due to the redundancy in the transmission of the same object detected by different sensors. The latter contrarily performs the fusion operation and derives a single object description for the detected object with the cost of higher computational complexity and delay.

Further, the sensor fusion process itself can be performed either at low-level or high-level. In low-level object fusion process, the raw sensor data from multiple sensors are fused directly. In high-level object fusion process, the raw sensor data is processed individually, and the obtained object data is later fused based on the ITS-S manufacturer specifications. The Technical Report has preferred low-level fusion process over high-level fusion process. As different manufacturers may have different fusion specifications, the higher-level fused object dynamics may be error-prone. For example, the obtained objects may differ in the two-dimensional spatial information which may affect the coordination process at the receiver node.

The processing of the detected objects at the receiver side also influences the data format. For example, the dynamics of the detected objects are derived at the receiver side based on the local coordinates of the originator stations. This demands a coordinates transformation process to be integrated at the receiver side to map the received object descriptions onto its local coordinates system. To make the local coordinates of the originator stations available at the receiver node, they need to be added in the message. Additionally, to increase the consciousness of the detected object descriptions at the receiver node, information about the sensors utilized by the originator station and their capabilities is also integrated in the message.

2.1.2.1.2 Message Format

The current structure of the CPM includes an ITS PDU (Packet Data Unit) header and 4 types of containers (as shown in Figure 8): a Management Container, a Station Data Container (these two containers form the Originator Station Container (OSC)), one or more Sensor Information Containers (SIC), and one or more Perceived Object Containers (POCs) [34]. The ITS PDU header was specified in [35] and includes Data Elements (DE) such as the protocol version, the message ID and the station ID. The Management Container (MC) is mandatory in the CPM and provides basic

information about the originator station including its position and type. The Station Data Container (SDC) is optional and includes additional information about the originator. It differentiates the originator vehicle and RSU and specify its additional properties. The Sensor Information Container is optional and includes details about the sensor properties. The Perceived Object Container is optional and specifies the dynamic state and properties of a detected object(s).

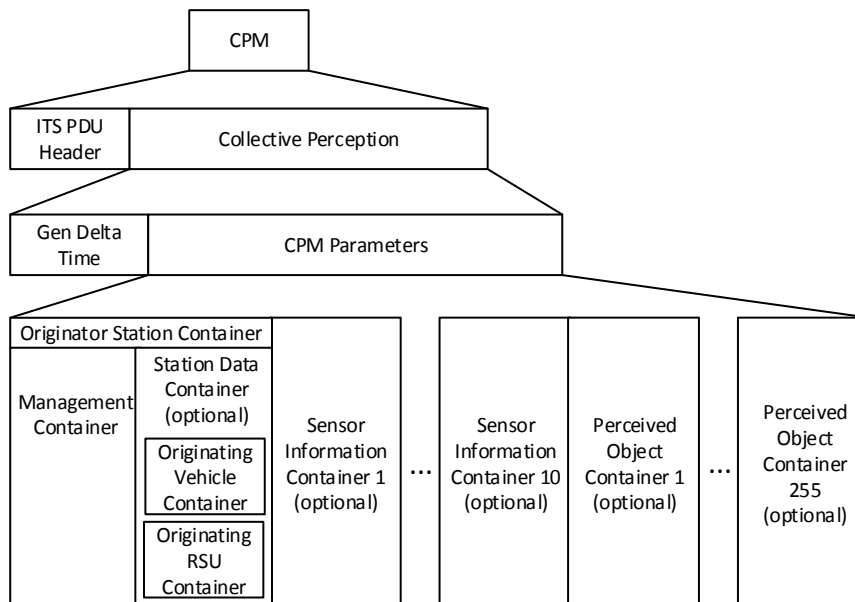


Figure 8. CPM General Structure (ETSI TR 103 562-v0.0.15)

2.1.2.1.2.1 Originating Station Container

The OSC includes properties and specifications about the originating ITS station that is required at the receiver ITS station to perform the necessary sensor data fusion and the coordinate transformation process. The OSC contains an MC and an SDC container. The MC contains information about the originator ITS station reference position and provides the horizontal position accuracy with a predefined confidence level. It also contains the Station Type that informs about the type of the originator ITS station as specified in [35] and that can be a vehicle or a RSU. The MC also includes the Action ID that is used to identify a set of objects distributed in consecutive CPMs and enables to track the objects in space and time.

Since both the vehicle and RSU ITS stations can generate the CPM, the SDC is defined as a choice between the Originator Vehicle Container (OVC) and Originating RSU Container (ORC). In case of vehicle ITS stations, the OVC contains mandatory and optional Data Fields (DFs) to describe the attributes of the vehicle dynamics such as heading, speed, angle and many more. In case of RSU ITS stations, the ORC has the choice between two DF parameters: Intersection Reference ID or Road Segment ID. These DF parameters are derived from the existing MAPEM (MAP (topology) Extended Message) [36]. These parameters are useful for the receiver ITS stations to match the received object dynamics to the geometric boundary of the defined intersection or road segment.

2.1.2.1.2.2 Sensor Information Container

The SIC describes the sensing capabilities of the originator ITS station. The SIC is used by the receiving ITS stations to derive the areas that are currently sensed by the originator ITS stations. A SIC includes the ID of a sensor, its type (e.g. RADAR, LIDAR or a sensor fusion system) and its detection area, among other Data Elements. It also specifies whether the sensing capabilities of the originator ITS station are from separate sensors or collectively from the sensor fusion. In the first

case, the SIC is recurrent for each sensor type and its sensing capabilities are reported individually. In total, a maximum of ten unambiguous SIC can be added in the CPM to report individual sensor properties. In case of sensor fusion, a single SIC is incorporated in the CPM and the general sensing capabilities of the collaborative sensors are reported.

The Data Fields included in the SIC are differentiated by two attributes namely Sensor Entry and Sensor Details (Table 1). The Sensor Entry is common includes the Sensor ID that defines a unique identifier, and the Sensor Type defines the type of sensor or the fused information. The Sensor Details subfield has a choice between defining the sensor properties of the vehicle (Vehicle Sensor) or RSU stations (Station Sensor Radial). These DFs specify the sensor measurement regions through defining sensor mounting position, sensor range and sensor opening angle. Other optional DFs in the SIC are the Stationary Sensor Polygon, Stationary Sensor Circular, Stationary Sensor Ellipse or Stationary Sensor Rectangle that specify the position and respective regions of sensors for objects detection. These optional DFs are particularly useful when several separate sensors are combined and projected as a single sensor module.

Table 1. Sensor Information Container (ETSI TR 103 562-v0.0.15)

Container		Data Fields (DF) / Data Elements (DE)	
Sensor Information Container (SIC)*	Sensor Entry	Sensor ID	
		Sensor Type*	
	Sensor Details‡	Vehicle Sensor	
		Stationary Sensor Radial	
		Stationary Sensor Polygon	
		Stationary Sensor Circular	
		Stationary Sensor Ellipse	
		Stationary Sensor Rectangle	
* Optional		‡ Choice	

2.1.2.1.2.3 Perceived Object Container

The POC is optional and describes the dynamic state and properties of the detected objects (Table 2). This container includes the sequence of Object Data elements that includes various mandatory and optional fields to describe the abstract dynamic properties of the individual detected object. A new POC is added for every detected object and a maximum of 255 POC containers can be added in the CPM. The Object ID DF in the POC provides an identifier for the individual detected object that can be used for tracking purposes. The Sensor ID DF in the POC specifies the corresponding sensor information that detects the object. Other mandatory DFs such as the Time of Measurement and Distance provide the state and space information of the detected objects with respect to the originator station reference point. The receiver is responsible to perform the process to transform the detected object dynamics with respect to its reference points. To classify the type of the detected object, a Classification mandatory DF is added in the POC container. Several optional DFs like Object Age, Object Confidence, Speed, Acceleration, Yaw Angle, Dimensions, Dynamic Status and

Matched Position will provide a more detailed description of the detected object and enable the receiver to coordinate and track the detected object in a three-dimensional space.

Table 2. Perceived Object Container (ETSI TR 103 562-v0.0.15)

Container	Data Fields (DF) / Data Elements (DE)
Perceived Object Container (POC)* Object Data	Object ID
	Sensor ID
	Time of Measurement
	Object Age*
	Object Confidence*
	Distance
	Speed*
	Acceleration*
	Yaw Angle*
	Planar Object Dimension*
	Vertical Object Dimension*
	Object Ref Point*
	Dynamic Status*
	Classification

*Optional

2.1.2.1.3 Message Triggering Conditions

The CPM generation rules define how often a CPM is generated by the originator station and which information (detected objects and sensors information) is included in the CPM. Periodic and dynamic policies are being investigated and discussed as part of the ETSI standardization process.

The periodic policy generates CPMs periodically every T_{GenCpm} . In every CPM, the originator station includes information about all the objects it has detected. The CPM should be transmitted even if no objects are detected. The periodic policy is being used as a baseline in the standardization process to compare its performance and efficiency with more advanced policies such as the dynamic one. With the dynamic policy, the originator station checks every T_{GenCpm} if the environment has changed and it is necessary to generate and transmit a new CPM. If it is, the vehicle also decides the objects that should be included in the CPM. A vehicle generates a new CPM if it has detected a new object, or any of the following conditions are satisfied for any of the previously detected objects:

- Its absolute position has changed by more than 4m since the last time it was included in a CPM.
- Its absolute speed has changed by more than 0.5m/s since the last time it was included in a CPM.
- The last time the object was included in a CPM was 1 second ago.

All new detected objects and those that satisfy at least one of the previous conditions are included in the CPM. If no object satisfies the previous conditions, a CPM is still generated every second, but only including the Management Container, the Station Data Container and the Sensor Information Containers (i.e. without any Perceived Object Container). It should be noted that these CPM

generation rules are an adaptation of the CAM generation rules [14] for detected objects. In addition, these generation rules are preliminary and only a first proposal (hence subject to possible changes in the final specifications) that must be now carefully analysed to understand its road traffic and communication implications.

2.2 TransAID Sensor Fusion

This section discusses the approach chosen in TransAID for the sensor fusion. Separate subsections discuss the road infrastructure at motorways with C-ITS data, camera sensor fusion and vehicle sensor fusion.

2.2.1 Sensor fusion at the infrastructure

2.2.1.1 Sensor fusion for motorway approach models

The merging assistant service in TransAID requires an accurate model of a section of approximately 1500m of motorway. This is demonstrated in Figure 9, which is taken from the TransAID Service 2 described in D4.1.

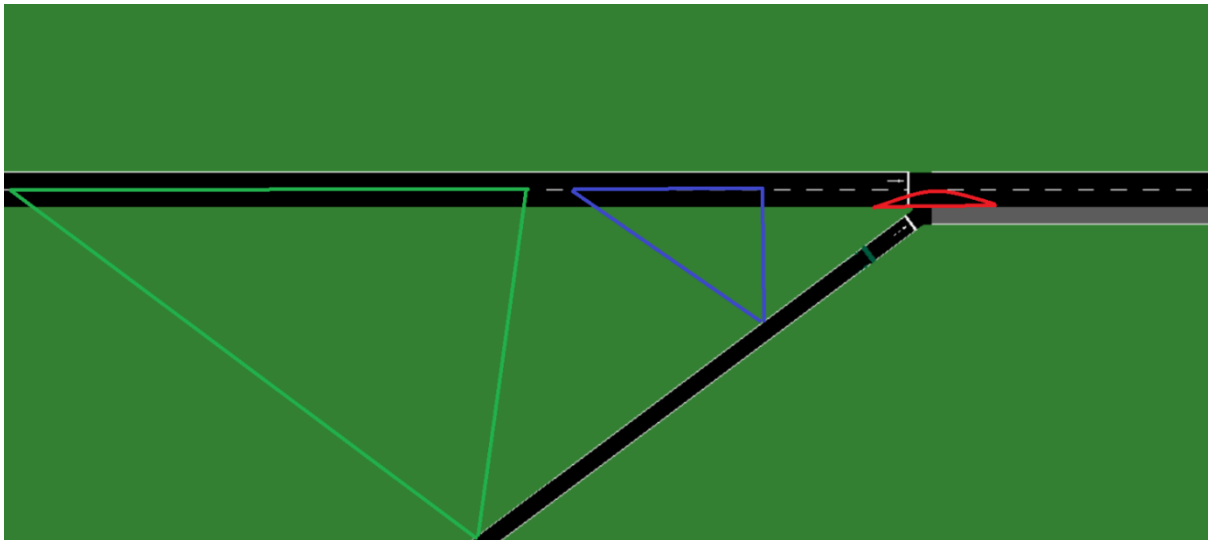


Figure 9. Detection area for gap selection for AV (red), LV (blue) and infrastructure assisted C(A)V (green).

New vehicles entering the motorway onramp get a gap assigned in the green area, which is a much bigger range than the red for CAVs without infrastructure assistance, or the blue estimate of what human drivers can oversee in LVs. After the gap selection, the vehicles keep being monitored to further guide onramp vehicles up to the merging area when they have changed lanes.

The model designed to support the merging assistant takes three data inputs and fuses them according to a certain hierarchy. This is illustrated in Figure 10:

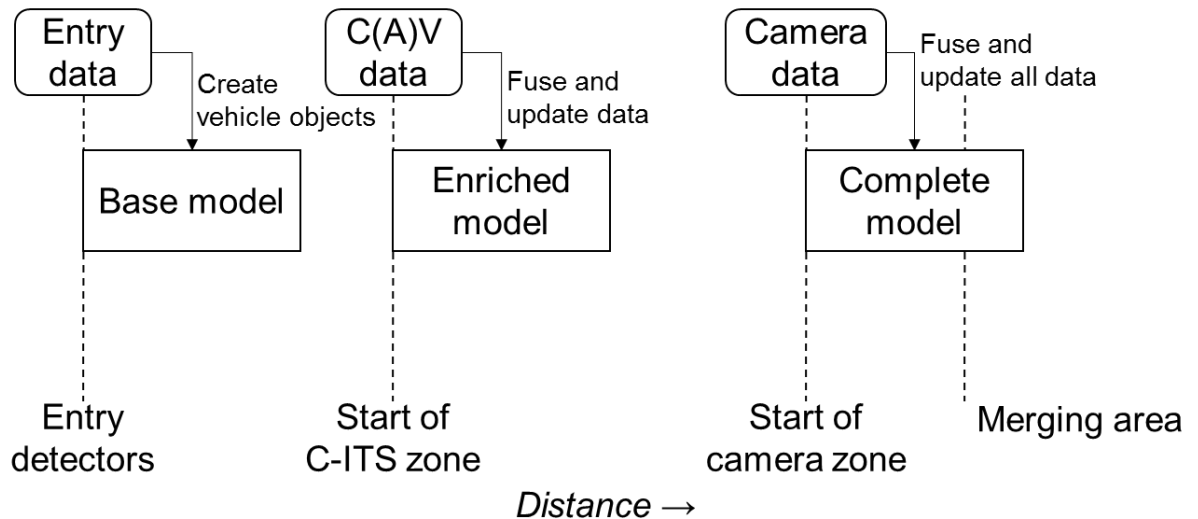


Figure 10. Traffic model for merging assistant.

The model starts with data from traditional sensors that can measure speed and occupancy. These are marked as “entry detectors” in the diagram and are usually traditional loop detectors that can only measure presence. Because they are double loop detectors at a small known distance, the speed can also be measured. Once a vehicle leaves such a sensor, it is processed as an entry for the model. Then every time step the vehicle is moved closer to the merging area according to its speed, keeping constraints of minimum following distance into account. This results in the base model in the figure.

A major problem with this base model is that the speed is assumed constant, while in reality especially human drivers vary their speed. Therefore, once C(A)Vs get in range of the RSU and CAM messages with speed and position data are received, corrections can be made to the model. The position of the C(A)V is compared to the positions of the vehicles in the base model and the closest is selected and subsequently flagged as C(A)V for future data fusion purposes. This is illustrated in Figure 11 below:

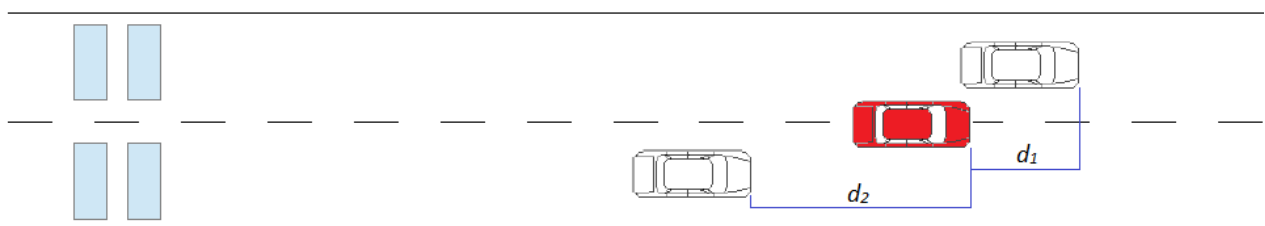


Figure 11. Data fusion of CAM with base model.

For example, when the base model indicates there is one vehicle at 500m from the merging area and one at 520m and a cooperative vehicle is detected at 505m, then the distance to the first vehicle, d_1 , is 5m while d_2 is 15m and it is likely the first vehicle is the C(A)V of which data is received. The data fusion also needs to define a maximum deviation before a new vehicle is created. Loop detectors have an accuracy of around 95-99%, depending on the maintenance state, so detections can be missed. Therefore, if there are no vehicles within the error margin, an extra vehicle will be created in the base model with the cooperative flag set. This flag is essential for future updates of the CAM message, because it links to the *stationID* and the model doesn't need to find the vehicle every time a message is received. This results in frequent updates to the speed and position for CVs. A problem is that CVs don't indicate their current lane, which reduces the accuracy of the fusing

algorithm. This is why the red measured vehicle in the figure is not yet placed in one of the lanes. Speed can also be a factor for the selection as it is unlikely for a fast vehicle to be on the outer lane when there are slower trucks in the model at that position. With more than two lanes, however, this becomes significantly harder. For CAVs, the current lane and the distance to the surrounding vehicles can also be updated. This makes data fusion easier and the relative distance to other vehicles is interesting to acquire data about unequipped LVs around. These concepts together result in the enriched model of the figure.

As a last step a tracking sensor is used to monitor the situation close to the merging area. This sensor has information on speed, position and current lane for all vehicles and will therefore give a complete model. This sensor is, however, expensive to install and maintain, so it is only used in the area where it is really necessary. With higher penetration rates of C(A)Vs the sensor is probably not required anymore. Data fusion of this sensor with the other data is implemented with the same principles. CVs with uncertainty of their current lane can be matched exactly according to their position, while LVs follow the principles of selecting the closest in the model, or creating a new vehicle. Lastly, this model also enables removing of LVs that were expected to be around, but are not there anymore. Vehicles will be held at the edge of the detection zone for a few seconds before being removed from the model.

This concept is further demonstrated in Figure 12. At $t = 0$ a new vehicle is detected by the tracking camera at the left lane. At that moment another vehicle was close to it, so this was easy to fuse. At $t = 1$, a vehicle on the right lane reaches the monitored area, but the tracking camera does not see it yet. Therefore, until $t = 3$, the vehicle is held there in the model. The vehicle behind it, is also held, but at a larger distance to keep realistic and safe car following distances in the base model. At $t = 4$ (not in the figure) the 2nd vehicle would have reached the monitored area and at the same time the other vehicle timed out and is removed. At $t = 7$, (last situation in the figure), the tracking camera detects a vehicle on the right lane, which is fused with the only remaining vehicle that was held at the edge of the monitored area.

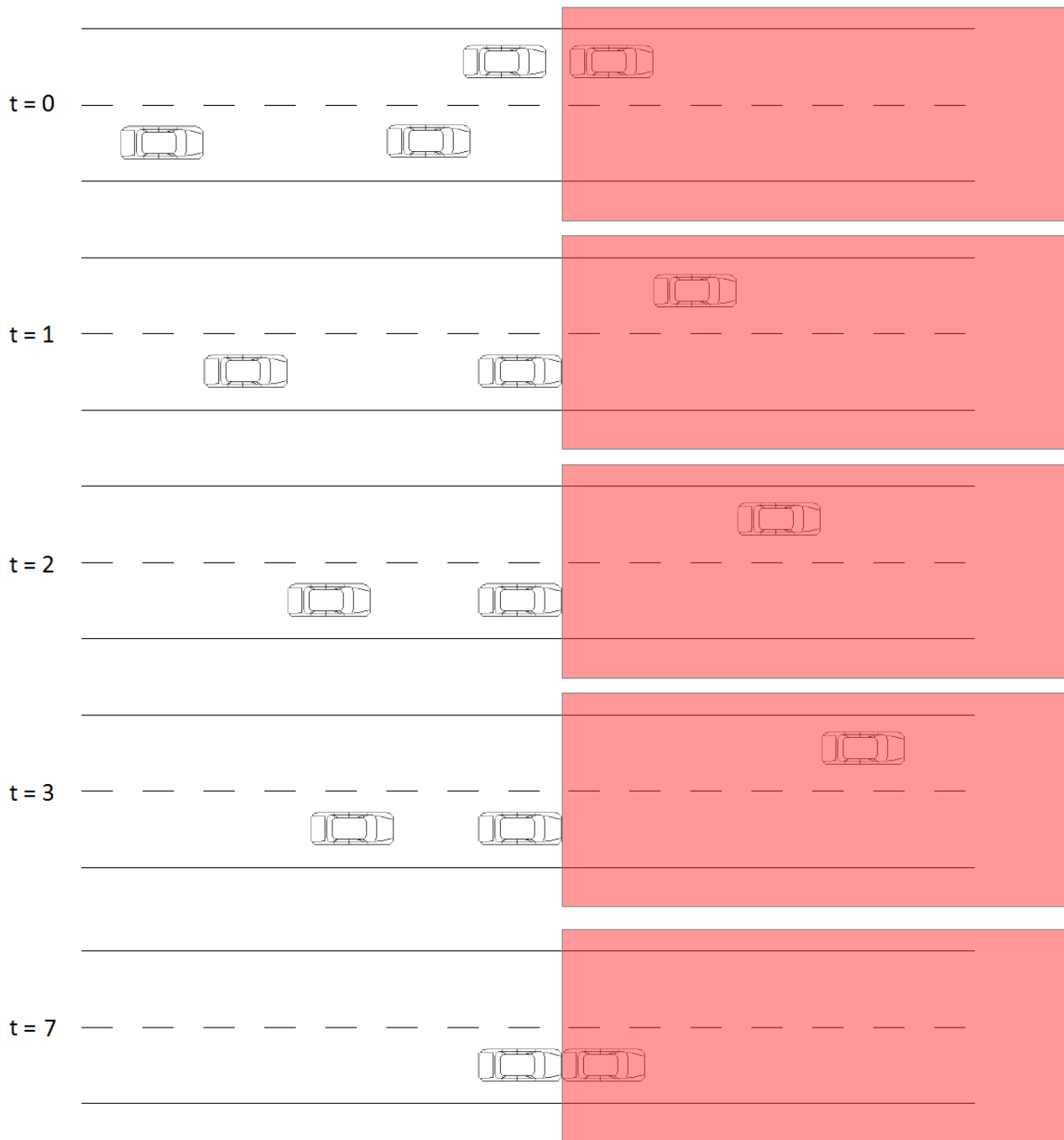


Figure 12. Data fusion concepts with tracking camera.

2.2.1.2 Enabling sensor fusion with road-side camera infrastructure

The camera RSU generates object trajectories from video sequences, converts them into station-relative 3D coordinates and generates CPM to publish them via V2X. As illustrated in Figure 13, input is a sequence of camera images which are real-time processed by object detection and tracking modules. First, the *object detection* module generates hypotheses about objects as cars, cyclists, or pedestrians being denoted as bounding box with confidence value in the image frame. The following module *optical flow* estimates image feature point trajectories describing the visual movement characteristics of visually trackable (i.e. textured and identifiable) image regions around these points. Together with the object bounding boxes, the *object tracking* module combines them into object trajectories, which means unique (re-)identification of objects over time and the

estimation of their trajectories in the image frame. Finally, the *back-projection* module generates metric and scaled 3D object trajectories relative to the RSU. For this, intrinsic and extrinsic camera calibration is required. Based on this 3D object data, the *V2X communication interface* is used to generate and transmit e.g. CPM.

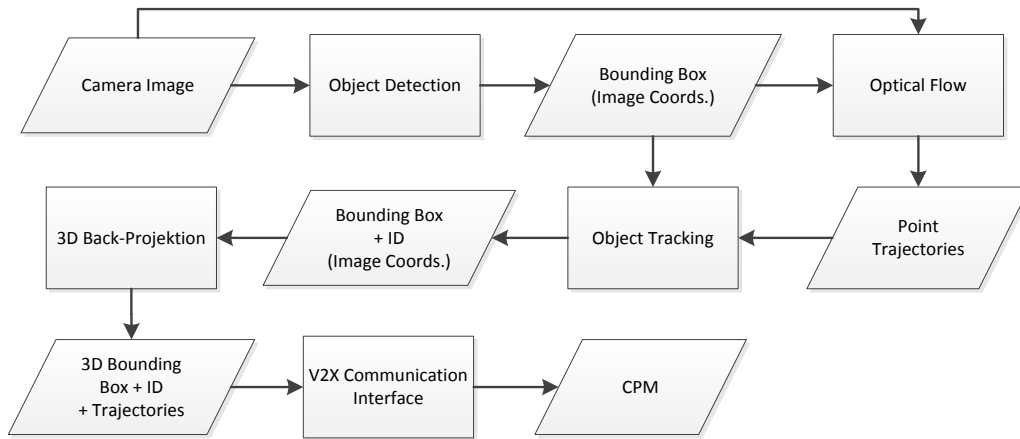


Figure 13. Overview of the infrastructure-based software components.

A visualization of the output is shown in Figure 14. The image shows object detection together with color-coded unique identifiers that will remain over time for each object. With the usage of optical flow measurements and subsequently the prediction of visual movements, detection errors can be compensated. For example, the cyclists in the lower right image region (IDs 47, 145, 177) are successfully tracked also on partly occlusions while they are moving behind a queue of driving and parking cars.

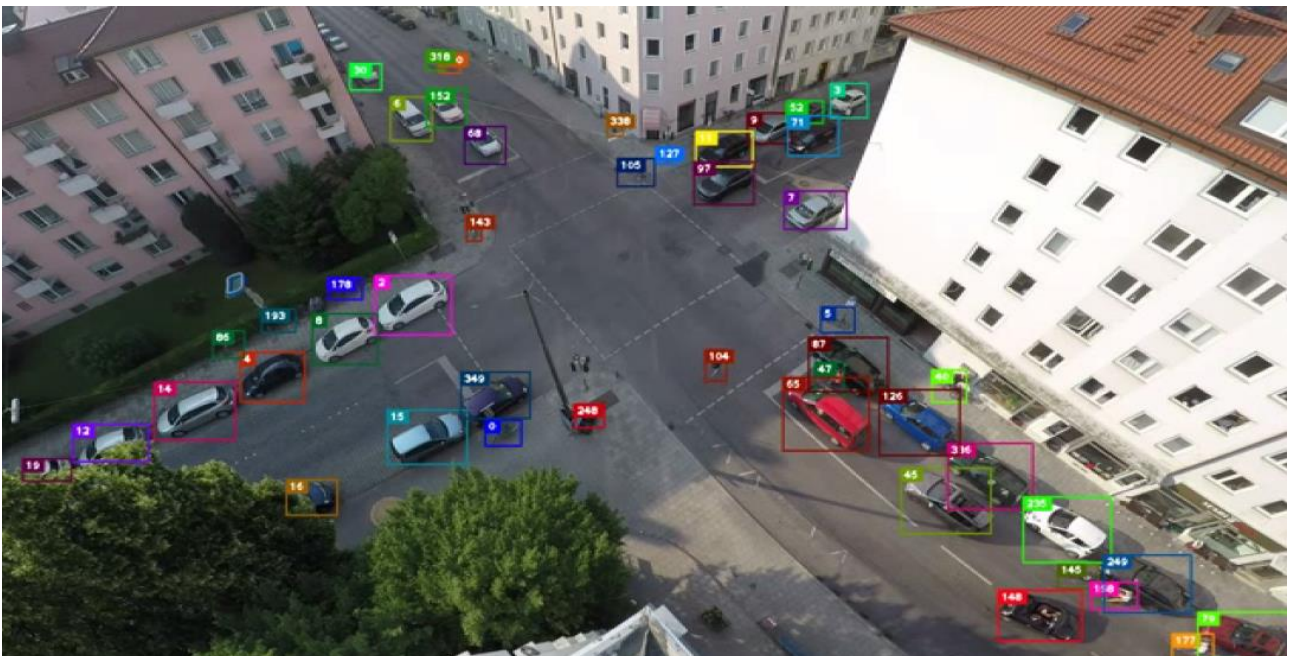


Figure 14. Road intersection scene with identified and tracked objects overlay.

2.2.1.2.1 Object detection

Current state-of-the-art methods are based on Convolutional Neural Networks (CNNs) [37]. Within the overall system, a software module was integrated which uses CNNs by using the TensorFlow Object Detection API [38]. This library is a widely used deep learning framework, and the pre-trained models provided are within a wide spectrum between efficiency and accuracy. Figure 15 shows the output of two CNNs of different complexity. In the upper image, a rather small *MobileNetV1* with a run time of 56 ms (for this image) is used. The lower image shows the output of *ResNet 101* with a run time of 106 ms. The latter network is slower but can detect all the objects.



Figure 15. CNN-based detection result with backbone *MobileNetV1* (upper image) and with backbone *ResNet 101* (lower image). Image source: KITTI dataset [39].

2.2.1.2.2 Optical flow

This module generates feature point trajectories over the image sequence. The implemented method is based on the feature detector FAST [40] which is applied on every image. For every significant image point (i.e. with re-identifiable region around the coordinate), the trajectory is tracked, or a new trajectory is initialized if the feature point is new. Features too close to existing trajectories are suppressed to limit its number. Additionally, feature identification can be limited to image regions of interest, i.e. where object hypotheses exist. This leads to further reduction of computation time. Optical flow, i.e. tracking from image to image is computed with the fast Lucas-Kanade method [41] or with dense optical flow [42]. In both cases, optical flow vectors are validated by backwards tracking. If tracking becomes unconfident, the feature point trajectory is terminated.

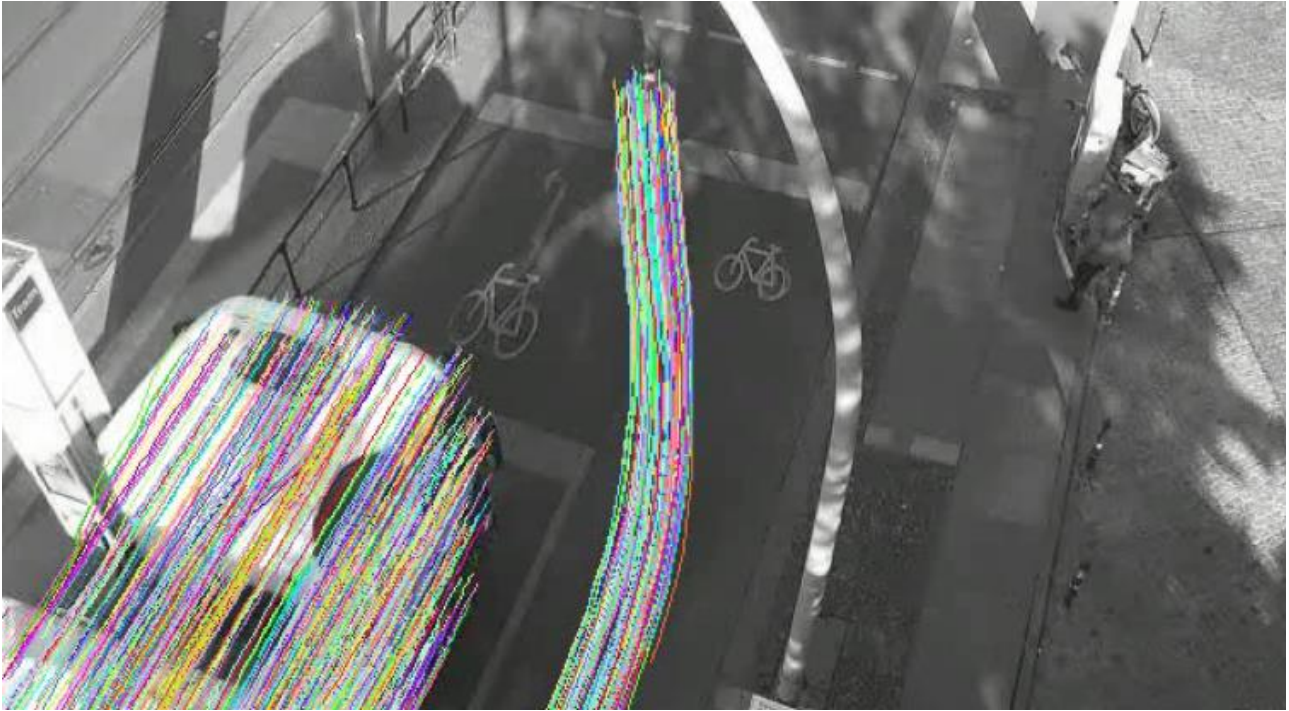


Figure 16. Color-coded visualization of feature point trajectories of a car and a cyclist.

2.2.1.2.3 Object tracking

Goal of this module is the estimation of object correspondences over time and the generation of unique identifiers for every object such that the single-image-based detections can be combined to trajectories over time. The task is modelled as optimization problem [43] which is illustrated in Figure 17. For a given input sequence, a graph is created where each detected object corresponds with a node. A source (s) and sink (t) is added which correspond to start and end of each trajectory. Thus, every s-t-path is one possible object trajectory. Since the number of objects is usually unknown, the solution of this object tracking problem is the set of non-overlapping s-t-paths with minimal cost. The constraint that the s-t-paths must not overlap ensures that each object is given maximal one identity.

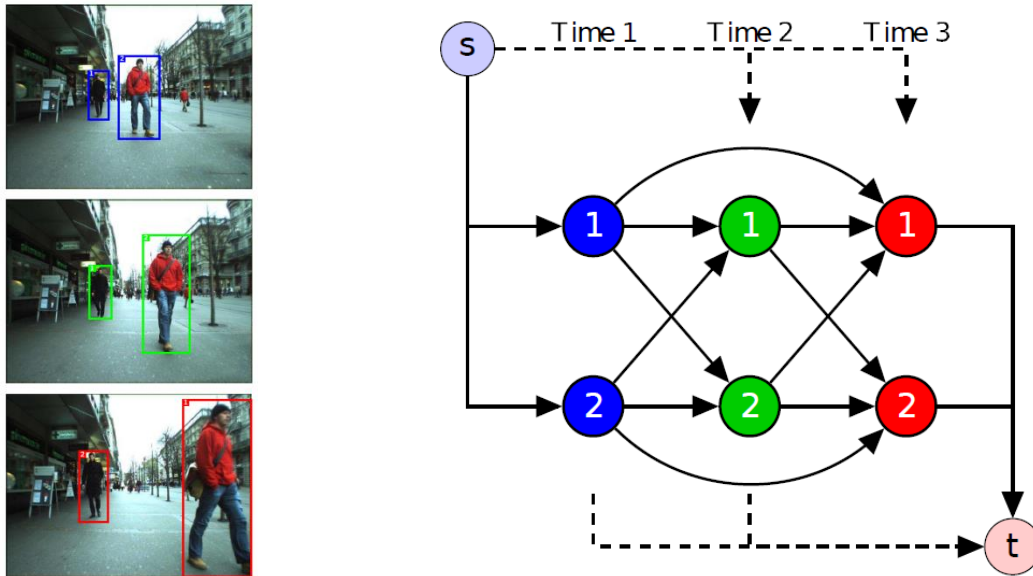


Figure 17. Illustration of a network flow graph over a sequence of three images (i.e. timestamps) with two detected objects. For every object, a node is added to the graph. Edges between nodes are possible object transitions between the images.

The goal is now to find an optimal solution with minimal cost. Such minimal-cost problems can be exactly solved in polynomial time. For the existing graph structure (no loops, edges with all the same direction), fast methods are existing that can solve the problem in linear time depending on the length of the image sequence [44]. The performance is mainly depending on the quality of input data (i.e. true positive object detection) and the precision of the cost function within the optimization. Figure 18 shows two detections of the same person in different images and illustrates how the transition cost can be calculated depending on the point trajectories from optical flow estimation. With the assumption that object detections from different images do likely refer to the same physical object if many feature point trajectories are within both object boundaries, the (inverse) cost is modelled as the amount of feature points that lie in the same corresponding object bounding box.

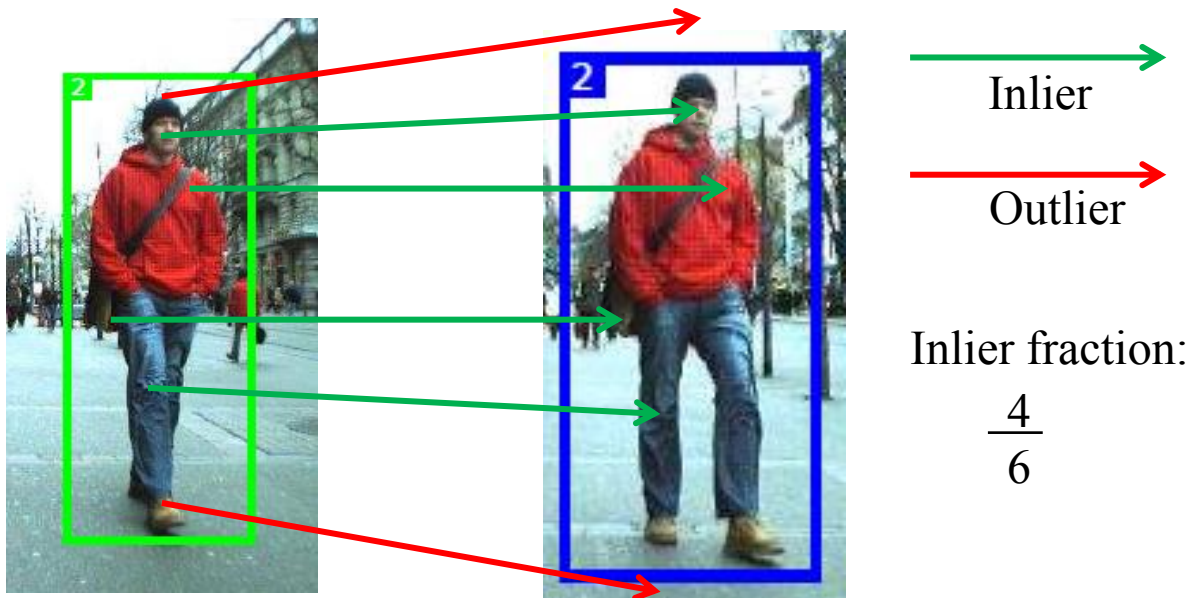


Figure 18. Calculation of movement cost terms. Object bounding boxes do probably refer to the same person if many optical flow vectors (i.e. visible movements in the image frame, marked as arrows) begin in one box and end in the other.

2.2.2 Sensor fusion at the vehicle

The TransAID project employs a hybrid sensor fusion strategy which contains a low-level LIDAR fusion module and an object-level fusion module. The low-level fusion module transforms the sensor data of multiple laser scanners into a common coordinate system. The object-level fusion module fuses in-vehicle sensor data with collaborative perception data from V2X messages. An overview of the processing pipeline is shown in Figure 19. In the following we give a brief description of the processing modules in this figure.

Low-level Data Fusion The vehicle has multiple laser range finders (mounted at the front and rear). The data acquired from these sensors is transformed into a common sensor coordinate representation within the low-level data fusion module. This transformation is performed based on extrinsic calibration (sensor position and orientation) which is available through a scene graph representation of the entire vehicle setup. The low-level data fusion module is also responsible to filter ground readings from obstacle readings. Ground readings are dropped from the point cloud as they impose no threat to vehicle automation.

Background Subtraction The registered obstacle point cloud is passed from the low-level data fusion module to a background subtraction module. This module identifies dynamic from static obstacles via scan matching: At each time step, the current point cloud is registered against a local map constructed from point clouds obtained at the previous time steps using a variant of the Iterative Closest Point algorithm [45] with initial guess taken from the ego-localization provided by a real-time kinematics device. Based on a configurable minimum object velocity, point correspondences between the map and the current scan are established using nearest neighbour search. Using this procedure, points with correspondence in the map are marked static and points without correspondence are marked dynamic.

Clustering & Tracking The clustering and tracking module partitions the cloud of dynamic points into clusters. In order to estimate object velocities, these point clusters are tracked over time using a Kalman filter. The final object hypotheses are formed by fitting an oriented bounding box to the raw point data.

Object-level Fusion The object level fusion module takes tracks from multiple sensor sources to construct a global track set. At this stage, objects from the in-vehicle sensor are fused with objects of other vehicles transmitted via V2X perception messages. The TransAID project is implementing a method based on [46] to establish track-to-track correspondences using a greedy local search. Object-level fusion operates at a fixed update rate, which can be different from the update frequency of different sensors. However, as individual sensor sources transmit full kinematic states (position, velocity, acceleration) rather than raw sensor data, trajectories of individual sensors can be interpolated or extrapolated to deal with asynchronous update frequencies.

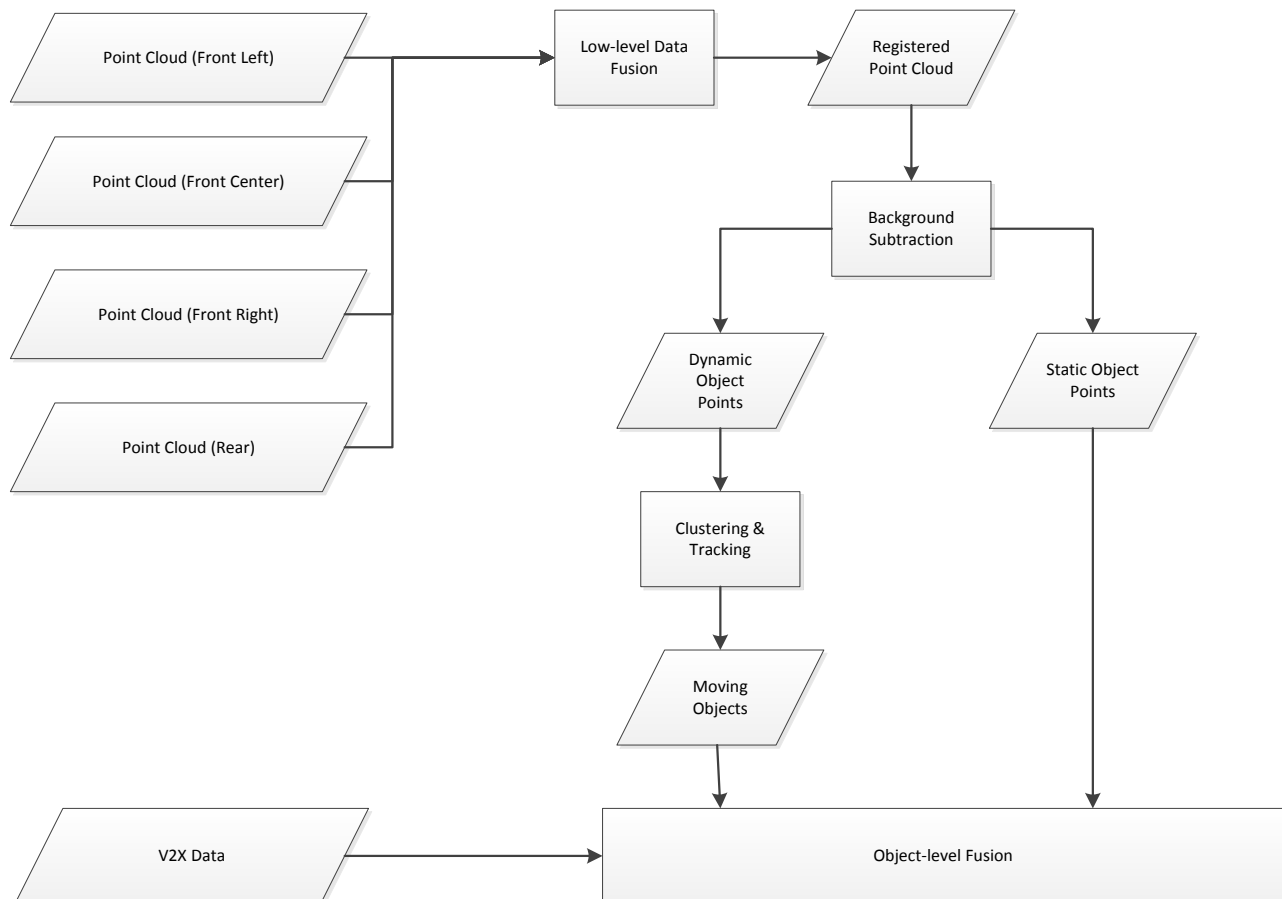


Figure 19. Overview of the TransAID project sensor fusion architecture.

2.3 Performance evaluation of ETSI Collective Perception

As part of the work that is being conducted in TransAID to contribute to the ETSI's CPS (see Annex A), this section shows an in-depth evaluation of the operation, communications performance and perception capabilities of the different collective perception message generation rules proposed in the ETSI CPS standardization [34] through simulations using NS-3. We have extended the NS-3 with a CPS component and different on-board sensors. The CPS component implements the periodic and the dynamic CPM generation rules. Two different periodic policies with 10Hz ($T_{GenCpm}=0.1s$) and 2Hz ($T_{GenCpm}=0.5s$) have been considered as a baseline in this study. In the dynamic policy, the T_{GenCpm} parameter has been set to 0.1s, so that the maximum CPM rate is 10Hz. The CPM size is dynamically calculated by the transmitting vehicle based on the number of containers in each CPM. The size of each container has been estimated offline using the current

ASN.1 definition of the CPM [34]. To this aim, we have generated 10^4 standard-compliant CPMs. Table 3 reports the average size of the containers that are used in this study. In our scenario, each vehicle is equipped with two on-board sensors looking forward [34]. Sensor 1 has 65m range and a field of view of ± 40 degrees. Sensor 2 has 150m range and a field of view of ± 5 degrees. The sensor shadowing effect (sensor masking) is implemented in the XY-plane, and we assume that the sensors can detect only the vehicles that are in their Line-of-Sight (LoS) [33]. We assume that the objects detected by the two sensors are fused.

Table 3. CPM Containers

CPM Container	Size
ITS PDU header	121 Bytes
Management Container	
Station Data Container	
Sensor Information Container	35 Bytes
Perceived Object Container	35 Bytes

The traffic scenario is a six-lane highway with 5km length and a lane width of 4 meters. We simulate two different traffic densities following the 3GPP guidelines for V2X simulations [47]. The high traffic density scenario (120veh/km) has a maximum speed of 70km/h, while the lower one (60veh/km) has a speed limit of 140km/h. For each traffic density, this study considers different speeds per lane. The speeds have been selected based on statistics of a typical 3-lane US highway obtained from the PeMS database [48]. We analysed the lanes speed of the highway for every hour within a single day and took the average speed for each individual lane. Vehicles created in the simulations have the dimension of 4.8m x 1.8m [33]. To avoid boundary effects, statistics are only taken from the vehicles located in the 2km around the centre of the simulation scenario. The configuration of the scenario is summarized in Table 4.

Table 4. Scenario parameters

Parameter	Values	
	Low traffic density	High traffic density
Highway length	5km	
Number of lanes	6 (3 per driving direction)	
Traffic density	60 veh/km	120 veh/km
Speed per lane	140 km/h	70 km/h
	132 km/h	66 km/h
	118 km/h	59 km/h

All vehicles are assumed to be equipped with an ITS-G5 transceiver (100% penetration) and operate in the same channel. The propagation effects are modelled using the Winner+ B1 propagation model following 3GPP guidelines [47]. The communication parameters are summarized in Table 5.

Table 5. Communication parameters

Parameter	Values
Transmission power	23dBm
Antenna gain (tx and rx)	0dBi
Channel bandwidth/carrier freq.	10MHz / 5.9GHz
Noise figure	9dB
Energy detection threshold	-85dBm
Data rate	6Mbps (QPSK 1/2)

2.3.1 Operation

Before analysing the performance and efficiency of each CPM generation policy, it is necessary to better understand their operation. To this aim, we focus first on the dynamic policy. Figure 20 represents for this policy the Probability Density Function (PDF) of the number of CPMs transmitted per second per vehicle under the two traffic densities. The number of CPMs generated per vehicle depends on the number of detected vehicles (i.e. traffic density) and on their dynamics (e.g. an object is included in a CPM every 4m). The speed of vehicles is higher for low traffic densities than for higher ones. As a result, vehicles satisfy more frequently one of the 3 conditions specified in Section 2.1.2.1.3 for the dynamic CPM generation rules (i.e., absolute position changes by more than 4m; absolute speed changes by more than 0.5m/s; 1 second since the last CPM transmitted), and vehicles generate more CPMs per second at low densities (Figure 20.a) than at high densities (Figure 20.b). However, not all vehicles generate CPMs at the same rate in a given traffic density scenario since the speed limit varies per lane (Table 4). It is interesting to analyse with more detail the high traffic density scenario (Figure 20.b). As previously mentioned, the higher the density the less CPMs are in general generated per vehicle since they travel at lower speeds. The vehicles that travel in the higher speed lane move at 70km/h or 19.4m/s. They will then change their absolute position by more than 4m every 0.21 seconds. Vehicles that detect this change generate then a CPM at 4.8Hz on average. However, Figure 20.b shows that there are vehicles that transmit 6-10 CPMs per second. This is the case because a vehicle generates a CPM as soon as one of the vehicles it detects changes its absolute position by more than 4m. If the detected vehicles change their absolute position by more than 4m at different times, the originator vehicle will need to generate different CPM messages. This explains why CPM frequency rates as high as 10Hz are observed in the highest traffic density scenario (Figure 20.b). It is also important to emphasize that the frequent transmission of CPMs reporting information about a small number of detected vehicles can result in a loss of efficiency due to a higher number of channel access attempts and redundant headers. Such efficiency might be improved by grouping in a single CPM the information of several detected vehicles in a short period of time.

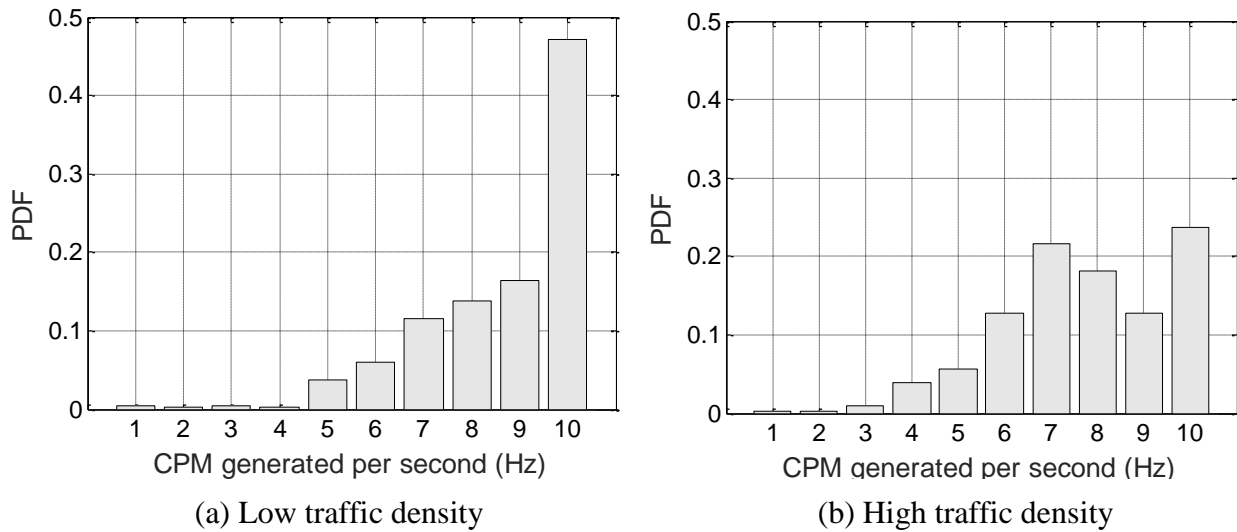


Figure 20. PDF (Probability Density Function) of the number of CPMs generated per second and per vehicle with the dynamic policy.

Figure 21 represents the PDF of the number of objects included in each CPM for the periodic and dynamic CPM generation policies under the two traffic densities. The figure shows that the periodic CPM generation policies augment the size of CPMs since they include a higher number of detected objects per CPM. This is the case because the periodic policies always include in the CPM all the detected objects, while the dynamic policy selects the detected objects to be included in a CPM based on their dynamics. As the traffic density increases, the number of objects included in each CPM increases with the periodic policies because more objects (i.e. vehicles in our study) are detected. However, Figure 21 shows that the traffic density does not significantly affect the number of objects included in each CPM with the dynamic policy. This is the case because the speed of vehicles decreases with the traffic density. As a result, vehicles change their absolute position by more than 4m less frequently. So even if we detect more vehicles due to the higher traffic density, the status of a detected vehicle needs to be reported in a CPM less frequently. The obtained results clearly show the benefits of the dynamic policy since it can adapt the number of objects included in each CPM to the traffic density and speed.

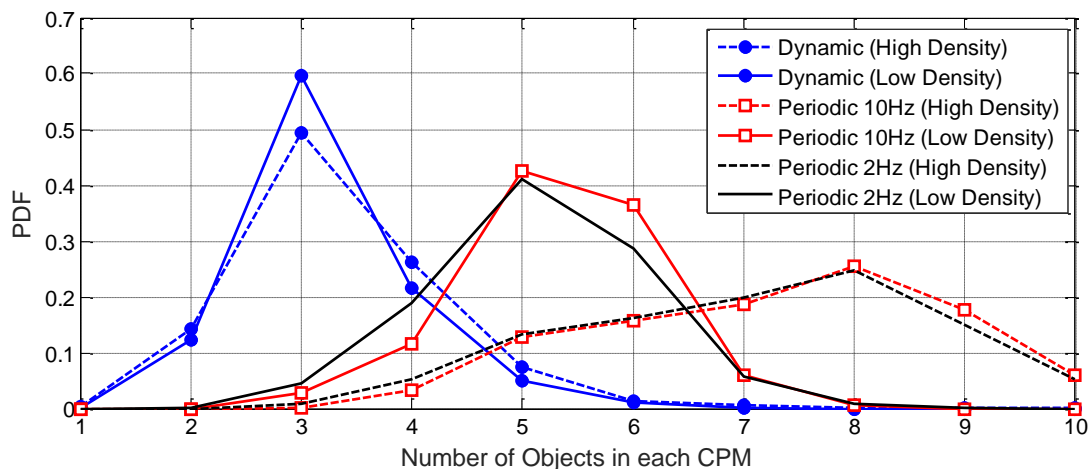


Figure 21. PDF (Probability Density Function) of the number of objects included in each CPM with the dynamic and periodic policies.

2.3.2 Communications performance

This section evaluates the impact of the CPM generation policies on the communications performance. To this aim, Table 6 shows the average channel busy ratio experienced when implementing each CPM generation policy under the two traffic densities. The CBR is measured by each vehicle every second. The CBR is a measure of the channel load, and it is defined as the percentage of time that the channel is sensed as busy. A high CBR value indicates that the channel is very loaded and hence risks saturating. If this happens, the communications performance degrades and the packet delivery ratio decreases [49]. Table 6 shows that the periodic policy operating at 2Hz is the one generating the lowest channel load. On the other hand, the periodic policy at 10Hz generates the highest channel load. The dynamic policy generates intermediate channel load levels (Table 6) in line with the results depicted in Figure 20 and Figure 21. These results showed that the dynamic policy generates between 4 and 10 CPMs per second, approximately, and reduces the number of objects per CPM compared to the periodic policies. Consequently, the dynamic policy increases the channel load compared to a periodic policy at 2Hz, but decreases it compared to the periodic policy at 10Hz. Table 6 also shows that the channel load and CBR increase with the traffic density. However, lower increases are observed with the dynamic policy than with the periodic ones. In particular, an increase in the traffic density augments the CBR experienced by the dynamic policy by a factor of 1.6, whereas it increases by factors of 2.2 (2Hz) and 1.9 (10Hz) for the periodic policies. This is again due to the same trend observed in Figure 21. When the traffic density increases, the speed of vehicles decreases and vehicles change their absolute position by more than 4m less frequently. As a result, vehicles generate less CPM messages. Therefore, the impact on the CBR with the traffic density is lower for the dynamic policy than the periodic ones.

Table 6. Average CBR (Channel Busy Ratio)

Policy	Traffic density	CBR
Periodic at 2Hz	Low	7.4 %
	High	16.5 %
Periodic at 10Hz	Low	33.4 %
	High	63.6 %
Dynamic	Low	25.4 %
	High	41.0 %

The channel load or CBR has an impact on the PDR (Packet Delivery Ratio). The PDR is defined as the probability of successfully receiving CPM as a function of the distance between the originating and receiving vehicles. Figure 22 plots the PDR of the periodic and dynamic CPM generation policies under the two traffic densities. The degradation of the PDR with the distance is due to the radio propagation effects. The PDR can also be degraded due to packet collisions or interference when the channel load is high. This effect is highlighted in Figure 22 where the arrows indicate the degradation of the PDR as a result of an increase of channel load and packet collisions when the traffic density increases. Table 6 already showed how the channel load increases with the traffic density. The resulting PDR degradation observed in Figure 22 is hence a consequence of the trends observed in Table 6. Following these trends, Figure 22 shows that the periodic policy operating at

2Hz achieves the highest PDR and the policy at 10Hz the lowest one. Figure 22 also highlights that the dynamic policy achieves a balance between the two periodic policies. However, it is yet to be seen whether the dynamic policy could improve the network performance and increase the PDR by avoiding the transmission of certain CPM messages without degrading the perception capabilities of vehicles.

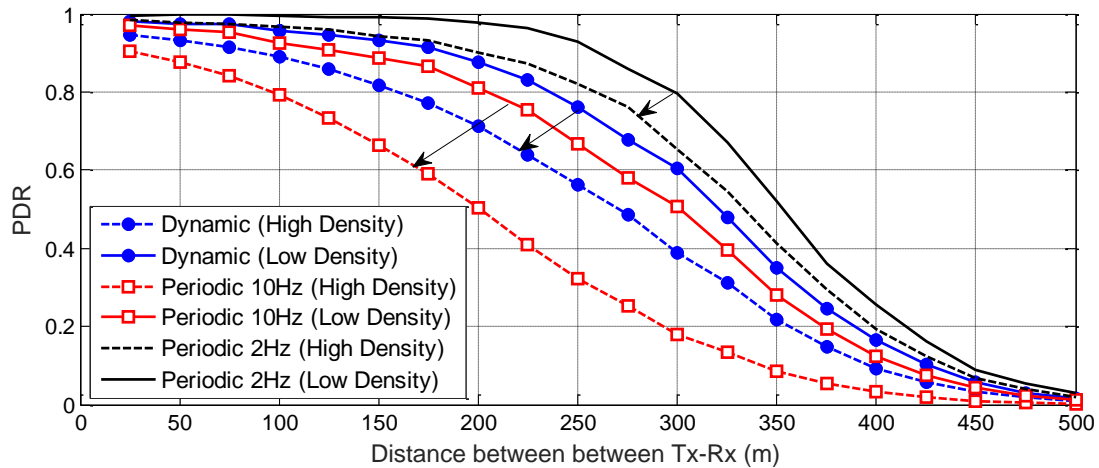


Figure 22. Packet Delivery Ratio as a function of the distance between transmitter and receiver.

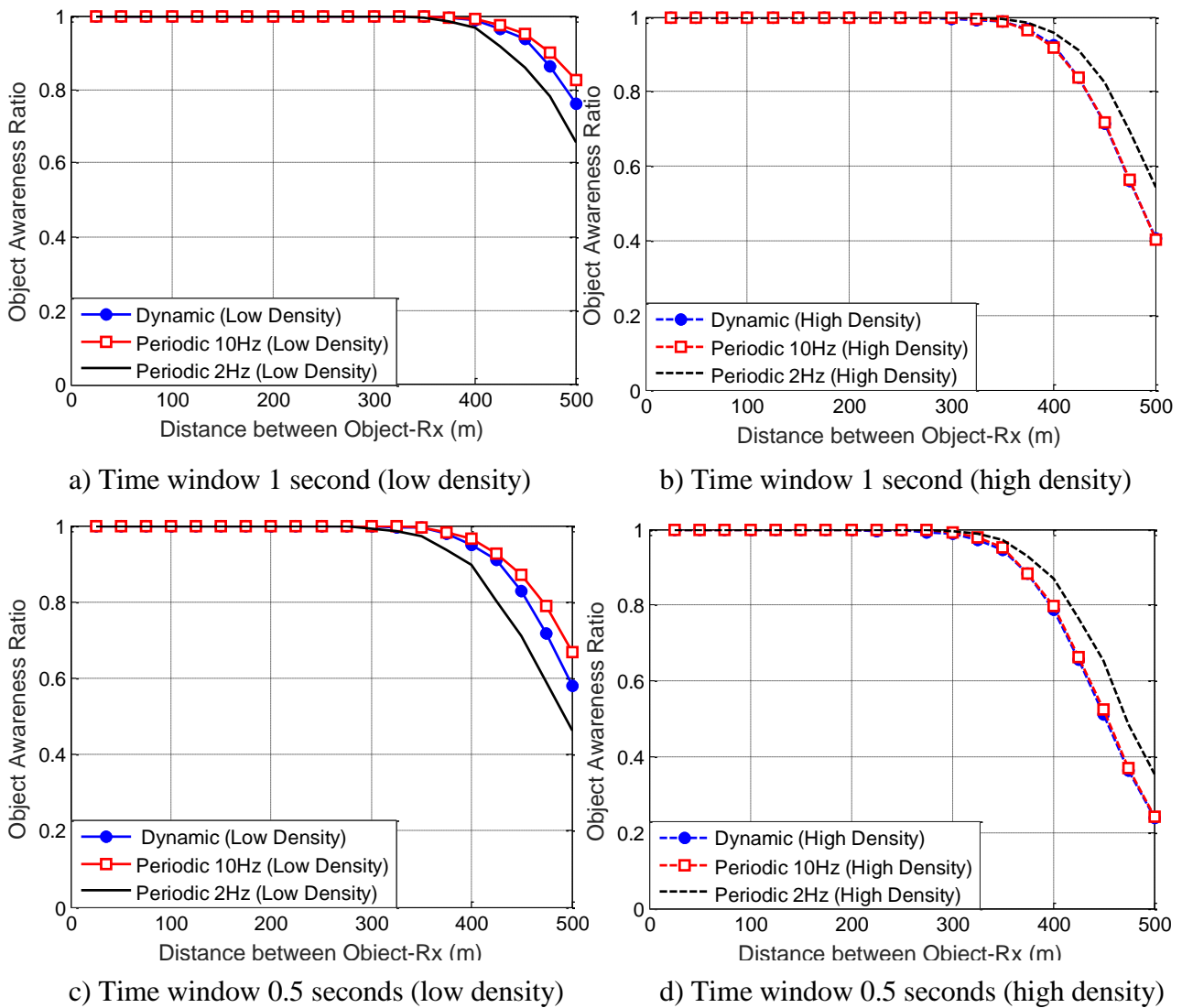
2.3.3 Perception capabilities

This section analyses the perception capabilities of vehicles as a result of the different CPM generation policies. To this aim, we define the Object Awareness Ratio as the probability to detect an object (vehicle in this study) through the reception of a CPM with its information in a given time window. We consider that an object is successfully detected by a vehicle if it receives at least one CPM with information about that object within a given time window. We computed the Object Awareness Ratio for three different time windows (i.e. 1s, 0.5s and 0.1s). Figure 23 depicts the average Object Awareness Ratio as a function of the distance between the detected object and the vehicle receiving the CPM. The results are shown for the periodic and dynamic policies and the two traffic densities.

The results obtained in Figure 23 show that when the time window is equal or higher than 0.5s all policies achieve a high object awareness ratio (higher than 0.987) up to 300m (see Figure 23 from a to d) independently of the traffic density. As shown in Figure 23.b and Figure 23.d, beyond 350m, the awareness ratio degrades under higher densities for the dynamic policy and the periodic policy at 10Hz. This is the case because of the higher CBR (Table 6) and lower PDR levels (Figure 22)¹. On the other hand, Figure 23.a and Figure 23.c show that from 350m a higher degradation of the awareness ratio is observed for the periodic policy at 2Hz under low traffic densities. This is due to the fact that at such distances the propagation effect becomes dominant when the traffic density is low (there are less packet collisions). All CPM generation policies experience the same degradation

¹ It is important to remember that the PDR is calculated as a function of the distance between two vehicles (originating and receiving vehicles), but the Object Awareness Ratio accounts for objects detected by any vehicle. In this context, the Object Awareness Ratio might refer to an object that is 300m away from the vehicle receiving the CPM, and the vehicle detecting the object and sending the CPM might be at 250m for example.

due to the propagation since it is not dependent on the channel load. However, propagation losses affect more negatively the Object Awareness Ratio for the periodic policy at 2Hz since this policy transmits less CPMs. To further study these effects, Figure 23.e and Figure 23.f show the Object Awareness Ratio for all the policies when the Time Window is set to 0.1s. In this case, the periodic policy at 2Hz cannot achieve a high Object Awareness Ratio performance even at short distances due to the low number of CPMs generated per second. The results reported in Figure 23.e and Figure 23.f show that only the periodic policy at 10Hz can achieve an Object Awareness Ratio close to 1 at short distances under this scenario. The dynamic policy, that compromises on CPM generation rate to reduce the channel load (Table 6) and therefore improves the communications performance (Figure 22) compared to the periodic policy at 10Hz, degrades the Object Awareness Ratio but still achieves a performance above 90% and 80% up to 250m and 225m under low and high traffic densities, respectively, for a time window 0.1 seconds.



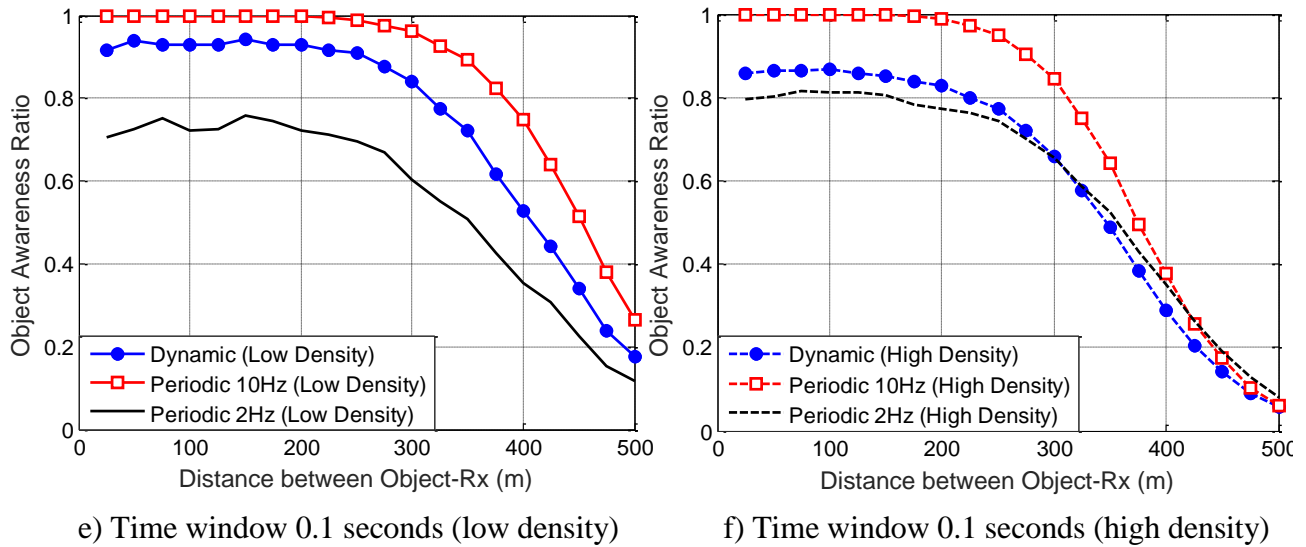


Figure 23. Object Awareness Ratio as a function of the distance between the detected object and the vehicle receiving the CPM.

The obtained results show that all CPM generation rules provide high Object Awareness Ratio performance. However, we have seen in Table 6 and Figure 22 that the CPM generation policies can generate non-negligible channel load levels that can degrade the communications performance and impact the network's scalability. It is hence necessary to evaluate whether the current CPM generation policies generate unnecessary redundancy about the present objects or vehicles in our driving environment. The Object Awareness Ratio is calculated considering all CPM messages received within the time window. Therefore, it is interesting to analyse the CPMs received that contain the same object. Figure 24 illustrates the number of updates received per second about the same object through the reception of CPMs. This metric is referred to as detected object redundancy and is depicted in Figure 24 as a function of the distance between the object and the vehicle receiving the CPM for both low (Figure 24.a) and high (Figure 24.b) traffic densities. The degradation observed in Figure 24 with the distance is a direct consequence of the PDR degradation reported in Figure 22. Figure 24.a and Figure 24.b show that the periodic policy at 10Hz provides around 55 updates (low density, Figure 24.a) and 63 updates (high density, Figure 24.b) per second of the same object at short distances (roughly, for short distances, i.e. PDR close to 1, this would mean that ~5 or ~6 vehicles are detecting the same object under low and high traffic densities, respectively). The dynamic policy can reduce this value to 33 updates (low density, Figure 24.a) and 28 updates (high density, Figure 24.b) per second and object without degrading the Object Awareness Ratio (Figure 23).

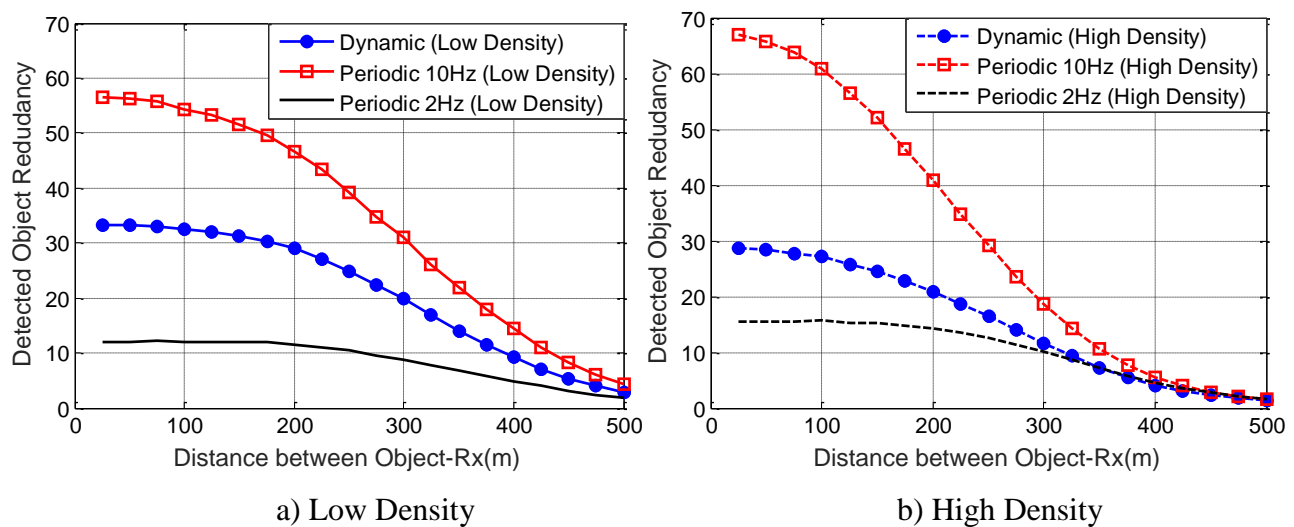


Figure 24. Detected object redundancy as a function of the distance between the detected object and the vehicle receiving the CPM.

Figure 24 showed the redundancy generated by the current CPM generation policies from the point of view of the vehicles receiving the CPMs. To further investigate the redundancy of CPM generation policies, Figure 25 analyses it from the point of view of the vehicle that sends the CPM messages. In particular, Figure 25 illustrates the number of updates per second a vehicle receives about the same object and that have been transmitted by the same sender. This metric is referred to as detected object redundancy per sender and is depicted in Figure 25 as a function of the distance between the object and the vehicle receiving the CPM for both low (Figure 25.a) and high (Figure 25.b) traffic densities. Similar to Figure 24, Figure 25 shows that the periodic policy at 10Hz provides around 6.8 updates (low density, Figure 25.a) and 6.2 updates (high density, Figure 25.b) per second of the same object at short distances from the same sender. The dynamic policy can reduce these values to 4.1 (low density) and 2.8 (high density) updates per second and object without degrading the Object Awareness Ratio (Figure 23).

The results reported in Figure 24 and Figure 25 show that the redundancy in the periodic policies at 10Hz and 2Hz increases with traffic density. On the other hand, the dynamic policy actually reduces the redundancy with the density. This is due to the fact that as the traffic density increases the vehicles' speed reduces, and this reduces the CPM generation rate as defined in the generation rules for the dynamic policy (see Section 2.1.2.1.3). Due to this fact, the dynamic policy can reduce the channel load (Table 6) and improve the communications performance (Figure 22). Despite the gains observed with the dynamic policy, it is yet an open issue whether the still high redundancy levels observed in Figure 24 and Figure 25 are necessary for a safe cooperative and automated driving or not. The dynamic policy could be modified to further decrease the redundancy and increase the robustness and scalability of the vehicular network as it is a key component to achieve the expected benefits of cooperative and automated driving.

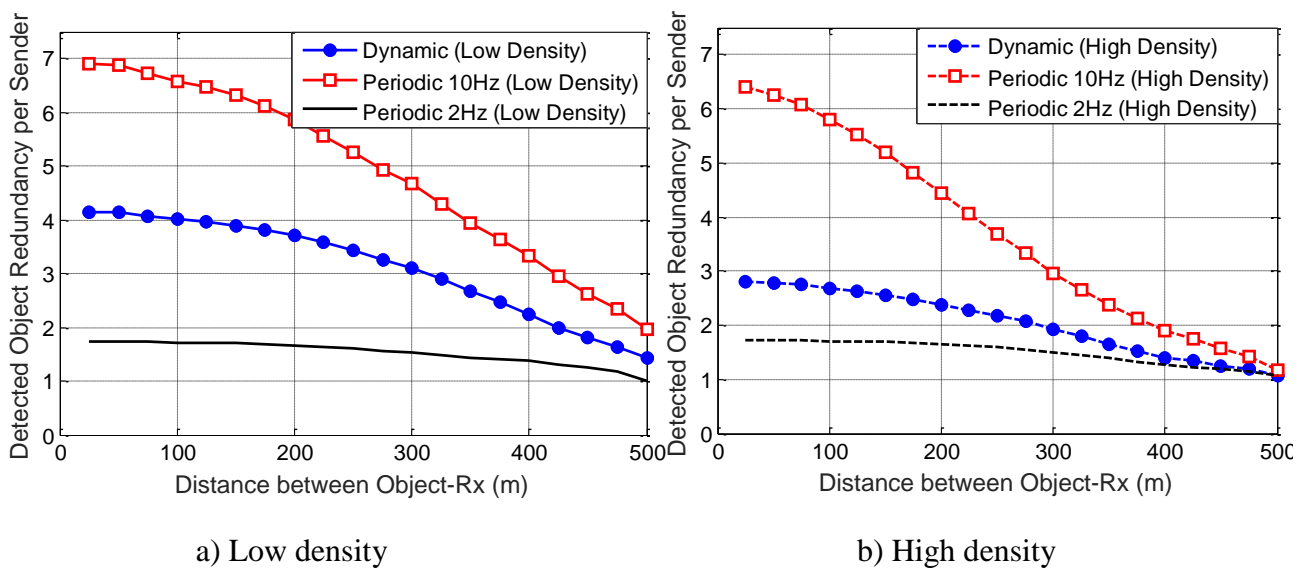


Figure 25. Detected object redundancy per sender as a function of the distance between the detected object and the vehicle receiving the CPM.

The value of collective perception or cooperative sensing depends on how timely or fresh is the information received about the detected objects. A vehicle cannot base its driving decision on outdated information. Figure 26 plots the time between two successive received CPMs with information about the same object or vehicle. The metric, referred to as the time between object updates, is represented as a function of the distance between the object and the vehicle receiving the CPMs for both low (Figure 26.a) and high (Figure 26.b) traffic density scenario. To further investigate the timeliness of the received information, Figure 27 plots the distance travelled by objects between two successive received CPMs with information about the same object or vehicle. In this case, the metric is named distance travelled between updates and is represented as a function of the distance between the object and the vehicle receiving the CPMs for both low (Figure 27.a) and high (Figure 27.b) traffic density scenario. It is important to emphasize that the CPMs including information about the same object or vehicle might be transmitted by different (multiple) vehicles.

Figure 26 shows that all CPM generation policies provide object updates below 0.1s for low density (Figure 26.a) and 0.08s for high density (Figure 26.b) up to 200m approximately. These time values are reduced to less than 0.04s (Figure 26.a) and 0.06s (Figure 26.b) with the dynamic policy. Alternatively, Figure 27 shows that all CPM generation policies approximately provide updates of objects that have travelled less than 4 meters (low density, Figure 27.a) and 2 meters (high density, Figure 27.b) up to 250 meters. These values reduce to 1.6 meters (low density, Figure 27.a) and 1.25 meters (high density, Figure 27.b) with the dynamic policy. It is important to note that for the two metrics (Figure 26 and Figure 27) the objects updates are fresher under high traffic density for the periodic policies. This is the case because the number of vehicles reporting about the same object increases with the traffic density. However, with the dynamic policy the time between object updates and the distance travelled between updates are increased when the traffic density increases, because vehicles reduce their speed and CPMs are generated less frequently.

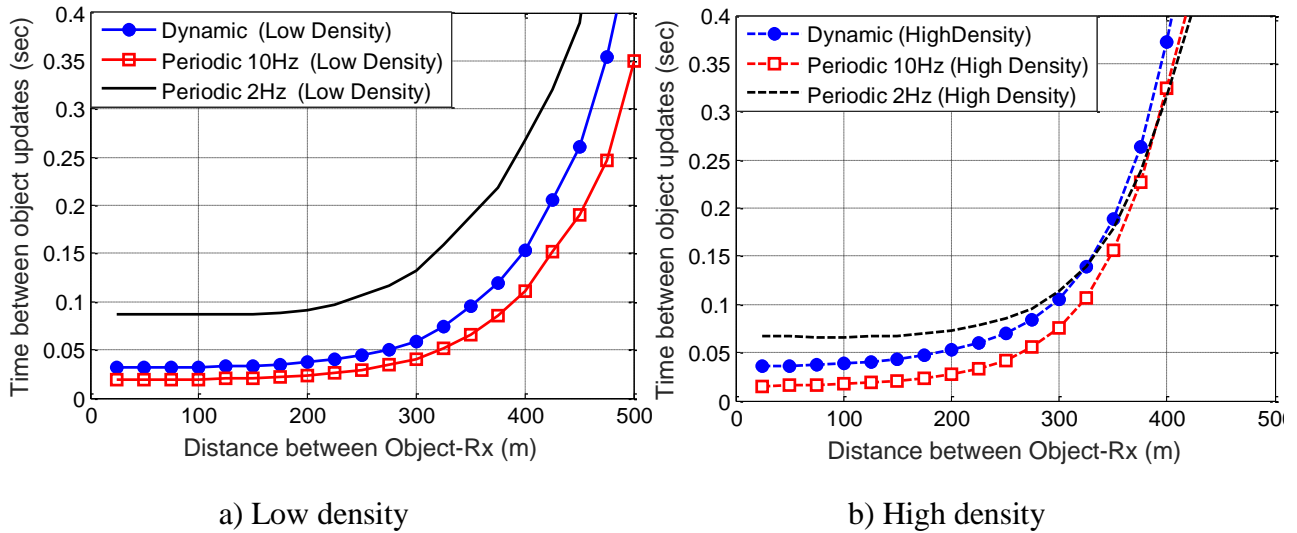


Figure 26. Average time between object updates as a function of the distance between the detected object and the vehicle receiving the CPM.

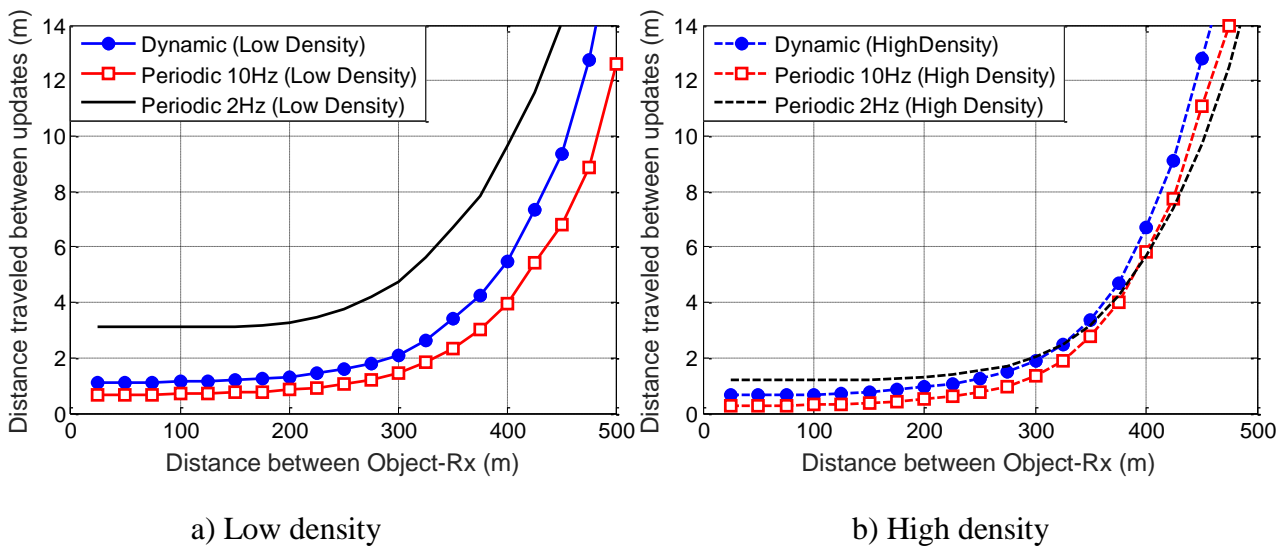


Figure 27. Average distance travel of an object between updates as a function of the distance between the detected object and the vehicle receiving the CPM.

3 Cooperative Driving

The introduction of autonomous vehicles is expected to improve traffic safety, reduce the fuel consumption of vehicles and improve the efficiency of traffic. As stated in Section 2.1.1.1, AVs will be equipped with different types of on-board sensors (e.g. cameras, LIDARs or RADARs) to perceive their environment. However, these sensors do not facilitate the dynamic interaction of vehicles, and AVs can only sense the environment and (try to) infer what other AVs are doing. V2X communications can facilitate the exchange of information about the driving intentions so that vehicles can coordinate their manoeuvres. Manoeuvre coordination allows vehicles to avoid errors in the estimation of other vehicles intentions, adapt their current trajectory based on the dynamics of neighbour vehicles and facilitates the coordination of the manoeuvres among vehicles. In the TransAID project, the road infrastructure supports the coordination of manoeuvres using V2I communications. Such support does not imply that the infrastructure will manage the manoeuvres of vehicles. Instead, TransAID defined five different services (see Deliverable 2.2 [50]) in which the infrastructure provides advice, notifications or information that vehicles can utilize to coordinate their manoeuvres.

3.1 State of the art

AVs are being designed to handle autonomously diverse traffic conditions and scenarios. However, automated driving might not always be possible (e.g. due to an unforeseen situation that the vehicle does not know how to handle) and a transition of control will be required [51]. Complex traffic situations with an elevated number of ToCs can negatively impact the traffic safety and efficiency [52]. Cooperative manoeuvring can help reducing ToCs and hence mitigating their negative effects. A cooperative manoeuvre is defined as the coordination of the manoeuvres of two or more vehicles for a safer and more efficient driving.

The cooperative manoeuvres defined so far are generally designed to solve specific traffic situations. For example, the AutoNET2030 project developed a cooperative lane change solution that is based on the reservation of (relative) space on the road [53]. Figure 28 shows the message flow of the cooperative lane change defined by the AutoNET2030 project. The vehicle that wants to perform a lane change (i.e. originating station) broadcasts a *Lane Change Request* message to find a vehicle willing to cooperate (i.e. target vehicle). Vehicles receiving this message will answer with a unicast *Lane Change Response* message informing whether they are able to cooperate or not. The originating station selects the most appropriate target vehicle and informs all vehicles in the lane change area about the selected target vehicle using a *Lane Change Announce* broadcast message that is periodically transmitted. Then, the target vehicle opens the required headway and both vehicles start the preparation for the cooperative lane change. Once the target vehicle is prepared, it sends a *Lane Change Prepared Notification* message to inform the originating vehicle that the lane change can be initiated. Then, the originating vehicle executes the cooperative lane change. Following the AutoNET2030 solution, Kesting et al. define in [54] a cooperative lane change manoeuvre that takes into account the neighbour vehicles. In particular, the cooperative lane change parameters (e.g. headway, longitudinal acceleration, etc.) are defined with the aim to minimize the induced overall braking of all involved vehicles.

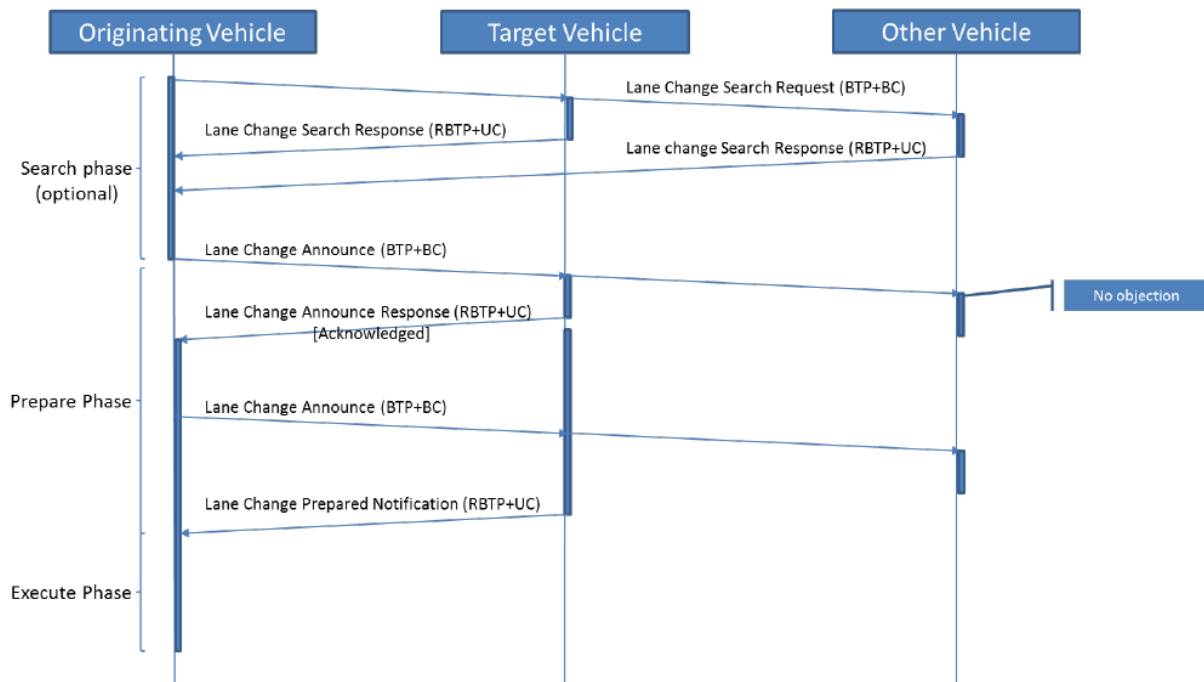


Figure 28. Message flow of the AutoNET2030 cooperative lane change [55].

The i-GAME project designed a cooperative manoeuvre solution for coordinating the merge of two platoons [56]. The proposed solution is based on a sequential basis where: 1) vehicles select a pair in the other platoon; 2) the selected pair creates a gap for the merge; and 3) the selected pair informs the originating vehicle that the lane change can be executed. Furthermore, the i-GAME project also designed a cooperative intersection passing manoeuvre based on the creation of virtual platoons of vehicles [56]. Vehicles approaching the intersection and willing to cooperate form a virtual platoon to establish the order in which the vehicles will enter in the intersection and the adequate gaps in order to ensure that all vehicles drive through the intersection in a safe way.

The approaches studied in UnCoVerCPS [57] are more generic and holistic towards systems development with formal guarantees and vehicle automation is one example application. One of the studied use cases is collaborative lane-change negotiation between two autonomous vehicles, and the review includes vehicle dynamics and control, collision avoidance, trajectory planning, and also V2V communication aspects.

The objective of the D3CoS project [58] was to develop methods, techniques and tools for system engineers and to embed them in industrial system development processes to support affordable development of highly innovative cooperative human-machine systems. Automotive-centred aspects were focused on cooperation between several vehicles (traffic perspective) and within one vehicle (on-board perspective) while the car acts as an agent controlled by a combination of human and artificial driver being in a social environment. With that, effects on traffic flow were investigated.

The previous solutions target specific traffic manoeuvres and might not be directly applicable to other manoeuvres. In contrast, Lehmann *et al.* [59] proposed a cooperative manoeuvre solution that is designed with the aim to be applied to every type of manoeuvre and scenario. The solution is based on the exchange of the planned and desired trajectories of the cooperative vehicles. Based on

these trajectories, vehicles can identify if there are potential conflicts with the trajectories of other vehicles and coordinate with them in order to define a cooperative manoeuvre.

3.1.1 ETSI approach on manoeuvre coordination

The ETSI Technical Committee on ITS has recently started a work item ('DTS/ITS-00184') on Maneuver Coordination Service that is in charge of defining concepts and messages which can be used to coordinate manoeuvres between vehicles [60]. The goal is to create a common framework for the implementation of cooperative manoeuvres. At the time of writing this document the standardization process is on its early stages. An agreement has not been settled on how the manoeuvres of vehicles shall be coordinated. Currently there is one proposal based on the work of Lehmann *et al.* [59]. The proposal is based on the use of V2V communications for the exchange of the planned and desired trajectories of vehicles. Based on this exchange of planned and desired trajectories, vehicles detect the need to coordinate their manoeuvres. Then, the involved vehicles define the type of coordination and finally, the cooperative manoeuvre is executed.

Following this proposal, all vehicles periodically transmit a maneuver coordination message including their planned trajectories. This allows identifying the need to coordinate manoeuvres when the computed desired trajectory intersects with the received planned trajectories of neighbouring vehicles. In addition, transmitting the vehicles' planned trajectories avoids others to do this estimation which can be subject to errors. Figure 29 shows an example of cooperative manoeuvre where vehicles exchange the planned and desired trajectories. In this example, the grey CAV wants to overpass a slow truck. In this context, the grey vehicle will need to compute its desired trajectory and detect whether this trajectory will generate any traffic conflict with either the desired or planned trajectories of surrounding vehicles. To do so, the grey CAV compares its desired trajectory with the trajectories received from surrounding CAVs. For each received trajectory, the grey vehicle computes if there is any potential conflict and if so, it computes which has the right of way. If the grey vehicle does not have the right of way, the desired manoeuvre cannot be executed without the coordination of the involved vehicles. This is exactly the case of the top subfigure of Figure 29 where the green vehicle has the right of way and intersects with the desired trajectory of the grey vehicle. When the grey vehicle detects this conflict, it also broadcasts within the MCM its desired trajectory. The green CAV receives the MCM from the grey CAV and considers the desired trajectory as a request for coordination since it also detects that the grey's CAV desired trajectory intersects with its planned trajectory. If the green vehicle is willing to cooperate, it will send a new MCM with an updated planned trajectory that is computed to allow the grey vehicle's desired trajectory (i.e. the overpass of the slow truck). When the grey CAV receives the green CAV's new planned trajectory, it realizes the green CAV is willing to allow its desired trajectory. Then, the green CAV's desired trajectory will become its planned trajectory and it will start the overtaking manoeuvre as its shown in the bottom subfigure of Figure 29. It is important to note that all other neighbouring vehicles are also aware of the cooperative manoeuvre taking place since all CAVs are periodically transmitting MCMs. An important aspect of this proposal that is being taken into account under ETSI is that the coordination of manoeuvres is governed by right of way rules. That means that if the vehicles that possess the right of way are not willing to cooperate, the manoeuvres will not take place and the desired trajectories will not be executed.

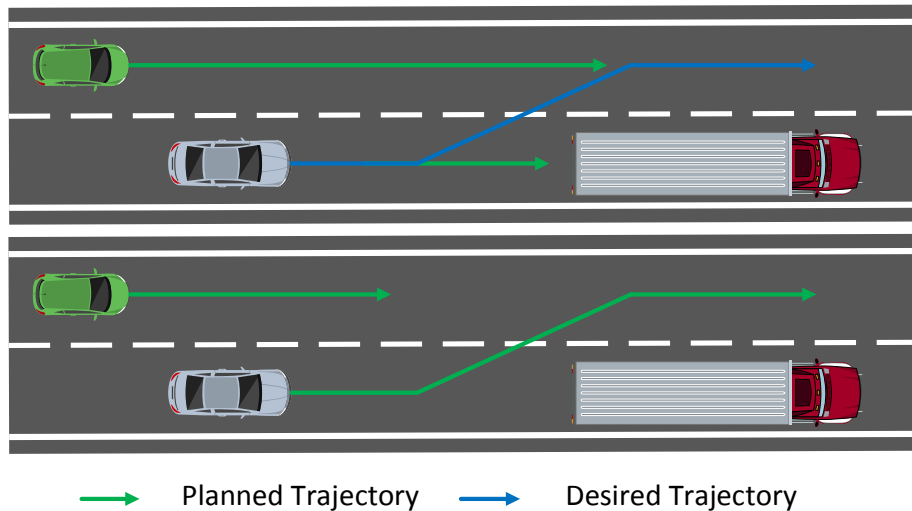


Figure 29. Example of cooperative manoeuvre.

3.1.2 TransAID proposal

As part of the work that is being conducted in TransAID to contribute to the ETSI's MCS (see Annex A), the TransAID project extends the current manoeuvre coordination approach under discussion at ETSI giving to the road infrastructure the opportunity to support manoeuvre coordination under certain scenarios and conditions. To do so, TransAID is defining a message structure for the MCM that varies with the type of originating station. Hence, the vehicles transmitting MCMs will employ the *VehicleManeuverContainer* container while the RSUs transmitting MCMs will employ the *RSUSuggestedManeuverContainer* container as specified in the Deliverable 5.1 [4]. Some of the benefits of using the infrastructure to support the manoeuvre coordination include:

Neutral coordination: currently, the road infrastructure is utilized to support the traffic management under particular traffic conditions such as traffic jams, peak hours or under the presence of roadworks. This approach which seeks supporting the management of multiple manoeuvres of different vehicles in a small area can be a challenge task for a fully distributed solution. Following this approach in the context of TransAID, the infrastructure can provide support, in the form of advice, to CAVs in the coordination of their manoeuvres so that vehicles can take better decisions. Service 1 defined by the TransAID project can serve as an example of this situation. In a scenario where roadworks block a part of the road, the infrastructure can provide suggestions about alternative paths to follow in order to overpass the roadworks and coordinate the manoeuvres of vehicles. This support from the infrastructure is expected to facilitate the merging of vehicles from different lanes and so to reduce the traffic disruptions. The support from the infrastructure could hence be considered as a natural evolution of current road traffic signalling systems.

Enhanced perception: any manoeuvre coordination approach is triggered when vehicles detect the need for coordination. In a fully distributed approach, the detection is in principle limited by the range of the V2V communications. On the other hand, RSUs can be strategically located at specific areas characterized by complex traffic situations that might require frequent manoeuvre coordination. In addition, the manoeuvre coordination supported by the infrastructure can benefit from the extended V2I range due to a higher elevation of the antennas and better propagation conditions. RSUs can obtain information about the traffic streams through the received CAM and CPM messages. Furthermore, the data of these messages can be combined with the data obtained

from road sensors installed in the area (e.g. inductive loops or cameras) to further improve the perception capabilities and increase the detection range. These benefits would allow that the infrastructure detects earlier the need for manoeuvre coordination, and hence it will increase the available time and space for the execution of the manoeuvre coordination in the vehicles. Additionally, the enhanced perception of the infrastructure, thanks to the fusion of different sources of information, allows the definition of cooperative manoeuvres that can be designed to improve the overall traffic in terms of safety and efficiency. This is particularly useful under mixed traffic scenarios where conventional, connected and automated vehicles coexist.

Coordination of multiple vehicles: Complex traffic situations could require the coordination of multiple vehicles. Coordinating multiple vehicles through the V2V distributed approach that is currently being considered at ETSI requires a pairwise and sequential coordination of the manoeuvres. That is, in order to coordinate the manoeuvre of three vehicles, two of them will define a cooperative manoeuvre and then the third one will coordinate with one of the other two. This increases the time needed to coordinate the manoeuvres of all vehicles and hence it has a potential negative impact in the road traffic. On the other hand, following the TransAID proposal, RSUs can act as a common (and neutral) coordination entity that provide advices, notifications or information that vehicles can utilize to coordinate their manoeuvres.

3.2 Message flow for the TransAID services

The TransAID project is defining a set of traffic management procedures and protocols to enable the smooth coexistence of automated, connected, and conventional/legacy vehicles, especially at Transition Areas. To this aim, TransAID follows a hierarchical approach that includes the implementation of control actions at different layers including centralised traffic management, infrastructure, and vehicles. In addition, TransAID has identified, so far, five different services and has proposed different solutions to address their Transition Areas (see Deliverable 2.2). The traffic management procedures employed for each Service rely on the communication between vehicles, and between vehicles and the infrastructure. The different messages employed by the TransAID services are defined in Deliverable 5.1. This section defines the V2X message flow between vehicles, and between vehicles and the infrastructure, that are needed to implement the traffic management procedures defined in the Deliverable 4.2 [5].

3.2.1 Message flow common to all TransAID services

All the TransAID services have in common the transmission of the cooperative awareness and collective perception messages that provide information about the vehicles and detected objects on the road. In particular, the CAM provides status information (e.g. location, speed, acceleration, heading, etc.) about the ego-vehicle while the CPM provides information about other vehicles/obstacles detected by the ego-vehicle. Both messages must be regularly/periodically transmitted following the message generation rules defined by ETSI. The generation rules for the CAM are defined at the ETSI standard EN 302 637-2 [14]. The generation rules for the CPM are currently under standardization [34]. The current standardization status of the CPM is described in Section 2.1.2.

The traffic management centre combines the information received in the CPM and CAM messages with other information extracted from road sensors. The fused information is used to create a virtual map of the traffic which is employed to define the traffic management procedures of the TransAID services.

3.2.2 Service 1: Prevent ToC/MRM by providing vehicle path information

The scenario of application of Service 1 is a three-lane road blocked by a roadworks zone as defined in the Deliverable D2.2 [50]. In order to overpass the roadworks zone, vehicles are temporarily allowed to use the bus lane (see Figure 30). This action may not be properly handled by CAVs, and therefore it could produce some ToCs or MRMs in the scenario. In order to keep traffic flowing smoothly, the TMC can assist these CAVs in planning their path around the roadworks zone. This is done by providing the CAVs with proper path information which allows them to use the bus lane at the adequate road section.

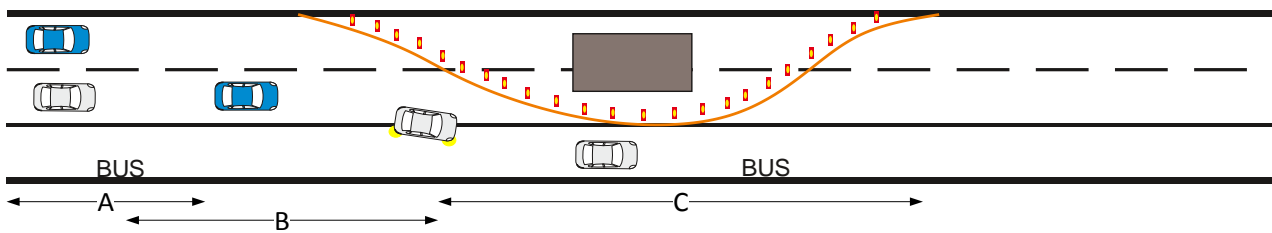


Figure 30. Scenario layout of Service 1 (A is the information transmission zone, B the merge zone and C the road works zone).

The traffic management logic of Service 1 is defined in the Deliverable 4.2. The TMC (regularly/periodically) broadcasts path information to the vehicles entering the information transmission zone (zone marked as 'A' in Figure 30). The path information refers to the bus lane that the CAVs can use. Upon the reception of this information CAVs will update their trajectory in order to move to the bus lane in the merge zone (zone marked as 'B' in Figure 30) to overpass the roadworks zone (zone marked as 'C' Figure 30). If necessary, the TMC will instruct CAVs in the merge zone that are already on the bus lane to increase the headway in order to facilitate the merging of other vehicles. CAVs will be advised to use the default headway again when they enter the roadworks zone.

The execution of Service 1 requires the exchange of messages between vehicles, and between vehicles and the infrastructure. Figure 31 describes the message flow or sequence of messages that need to be exchanged between vehicles, and between vehicles and the infrastructure, in order to execute Service 1 in the scenario defined in Figure 30.

First of all, the TMC (through the RSU) broadcasts the roadworks alert and the permission to temporarily use the bus lane to overpass the roadworks zone to all C(A)Vs in the information transmission zone (see Figure 31). To this aim, the TMC employs two different messages following the V2X message set defined in Deliverable 5.1. The DENM (Decentralised Environmental Notification Message) is employed to alert vehicles that the roadworks are blocking the road. Specifically, the *RoadWorksContainerExtended* container is employed, which gives information about the lanes closed by the roadworks (i.e., location/area that the roadworks zone occupies). The MAPEM is employed to inform C(A)Vs that the bus lane can be temporarily used by all types of vehicles in order to overpass the roadworks. Upon the reception of these messages, CAVs will compute again their future trajectories (planned and desired) taking into account the information included in the MAPEM and DENM messages. If the CAVs detect that they have to modify the current trajectory, they will send an MCM message to inform nearby CAVs and RSUs about the new planned trajectory.

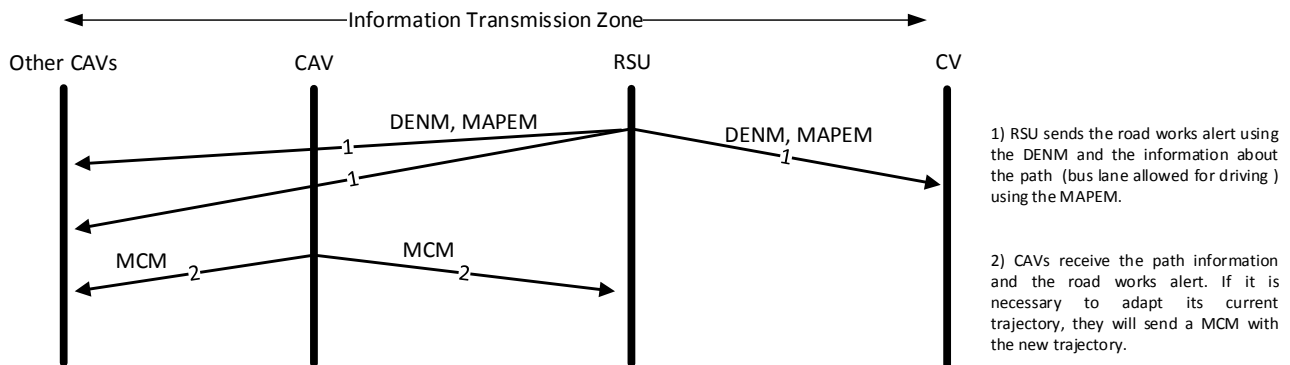


Figure 31. Message flow in the Information Transmission Zone.

In parallel to the transmission of the DENM and MAPEM messages shown above, the TMC monitors the vehicles that are in the merge zone (see Figure 32). If the TMC detects that there are vehicles in the left lanes that need to find a gap for merging to the bus lane, it will advise the CAVs in the bus lane to increase their headway. Thus, the gap between vehicles that are in the bus lane will increase and this will facilitate the merging of vehicles that are in the left lanes. The transmission of this advice will be done employing the *car following advice* object defined in the *RSUSuggestedManeuverContainer* container of the MCM message (see D5.1 [4] for details). Upon reception of the MCM, the CAVs that are located in the bus lane are expected to update their planned trajectories (i.e. increase their headway). This will trigger the transmission of an MCM message that includes the updated trajectory and the confirmation to the TMC that this CAV is willing to follow the advice. As a result, CAVs in the left lane(s) would be aware of the additional gaps that the CAVs in the right lane are creating. In addition, CAVs in the left lane(s) would update their planned trajectories accordingly. The change of the planned trajectory implies that these CAVs would also transmit an MCM with the new trajectory to inform the surrounding CAVs and RSUs.

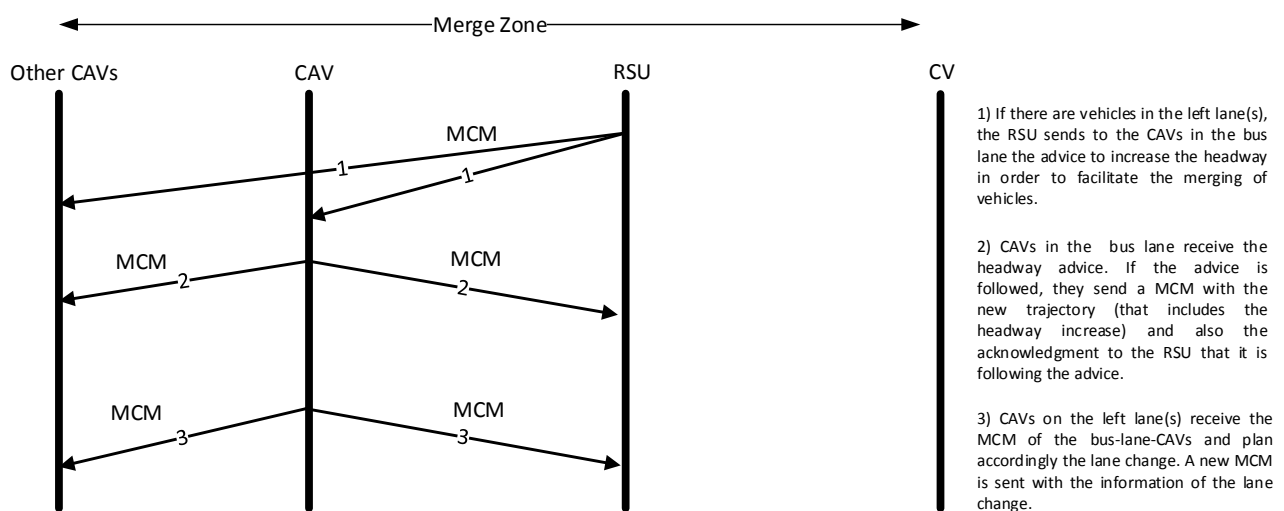


Figure 32. Message flow in the Merge Zone.

Finally, Figure 33 shows the exchange of messages between the TMC (through RSU) and CAVs that is used to set the headway to the default value. This message exchange happens when CAVs are entering the roadworks zone. At this point in time, the TMC sends an advice to the CAVs asking them to reset their headway to the default value (the default value depends on the type of vehicle). Again, this is done using the *car following advice* object of the *RSUSuggestedManeuverContainer* container of the MCM. The CAVs that receive this advice compute whether they have to modify their current trajectory in order to follow the headway advice. If this is the case, they would send a new MCM message indicating their new trajectory.

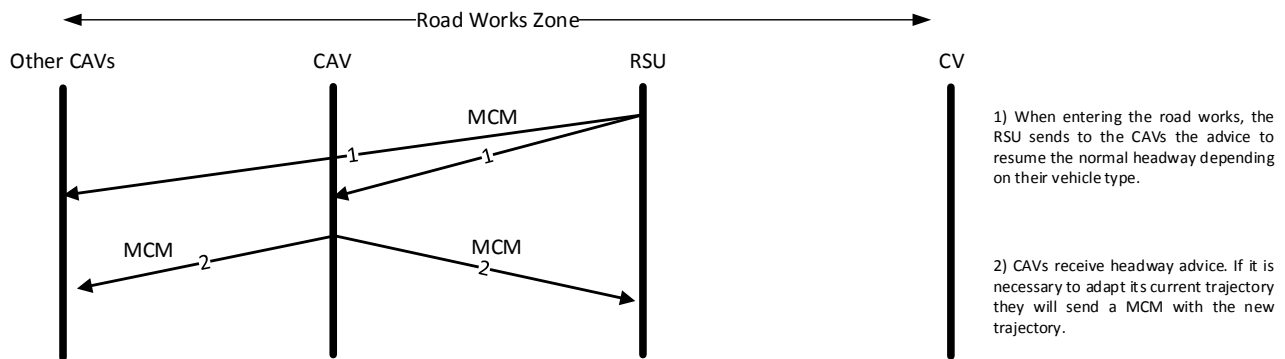


Figure 33. Message flow in the Road Works Zone.

3.2.3 Service 2: Prevent ToC/MRM by providing speed, headway and/or lane advice

The scenario of application of Service 2 is a two-lane road with an on-ramp lane on the right as defined in Deliverable D2.2. The RSU monitors the area and provides guidance to CAVs on the on-ramp lane to facilitate the merging process (see Figure 34). This is done by identifying the available gaps in the main road and providing the adequate speed advice to on-ramp CAVs in order to safely merge to the main road.

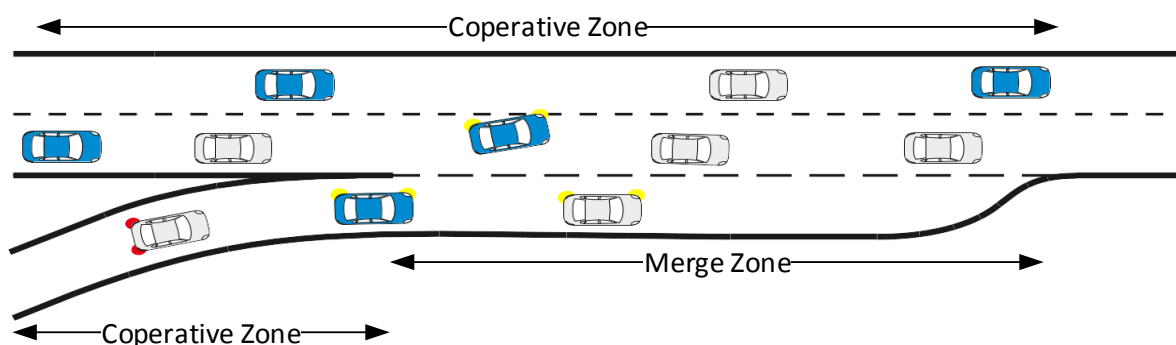


Figure 34. Scenario layout of Service 2.

The traffic management logic of Service 2 is defined in the Deliverable 4.2 [5]. The RSU monitors both, the vehicles coming from the (two-lane) main road, and the vehicles coming from the on-ramp road, that are approaching the merge zone. Then, the RSU computes the gaps available in between the vehicles located in the main road and evaluates whether these gaps are enough for the CAVs

coming from the on-ramp lane to perform the merge. If the RSU identifies some gaps in the main road, it sends individual speed advice to the on-ramp CAVs in order to offer guidance in the merging process. For those cases in which the RSU cannot identify a gap large enough to perform the merge, the RSU will advise those CAVs to do an early ToC and request the human driver to take over the merging process.

The following message flow describes the sequence of messages that need to be exchanged between the vehicles, and between the vehicles and the infrastructure, in order to execute Service 2 in the scenario defined in Figure 34.

As shown in Section 3.2.1, the RSU continuously monitors the whole area and gathers information about the vehicles (i.e. speed, position, ego-lane leader gap) using the received CAM and CPM messages. When a C(A)V enters the cooperative zone, through the inner lane of the main road, the RSU requests it to keep the current lane until the end of the Merge Zone. This is already a common measure at merging areas with a solid line on the left and a dashed line on the right of the lane separation. It creates space on the outer lane for merging and makes the model more predictable. The RSU performs this request to the C(A)V using the *lane change advice* and the *car following advice* objects defined in the *RSUSuggestedManeuverContainer* container of the MCM (see Figure 35). Upon the reception of this message, the C(A)V sends back an acknowledgement to the RSU using their next MCM. It is important to note that C(A)V do not have to modify their trajectories as the advice is to maintain their current lane. This simplifies the task of the RSU of computing the available gaps in the main road. Once these gaps are calculated, the RSU sends individual speed advice to the on-ramp CAVs to facilitate the merging. Again, this is done employing the *car following advice* object defined in the *RSUSuggestedManeuverContainer* container of the MCM. Upon the reception of this advice, the on-ramp CAVs modify accordingly their trajectories. This will trigger the transmission of an MCM message that includes the new trajectory and the confirmation that the CAV is willing to follow the speed advice sent by the RSU.

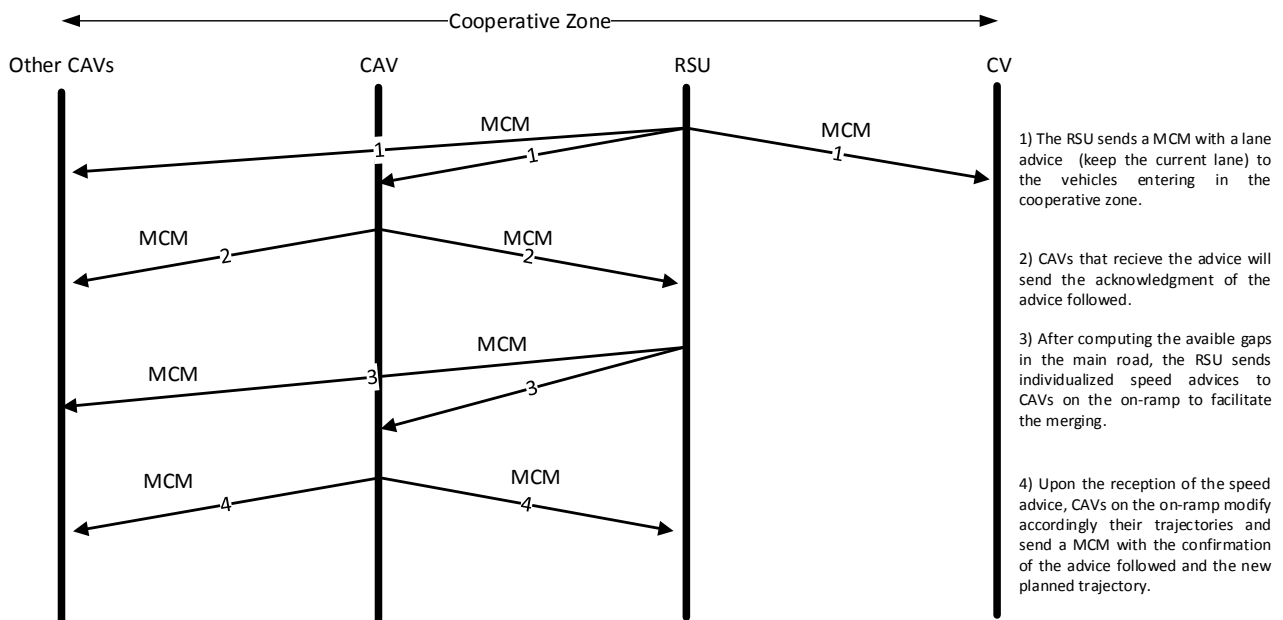


Figure 35. Message flow in the Cooperative Zone.

In order to guarantee that a safe merge process is performed, the RSU keeps monitoring the trajectories of the vehicles in the merge zone. In case no gaps are found in the main road, or the

speed advice sent by the RSU is no longer valid, e.g. because the intended gap was closed unexpectedly, the RSU requests the CAVs to perform a ToC (see Figure 36). Note that the ToC advice will be sent as soon as the RSU detects that the merging will not be possible (CAVs can receive the ToC advice in the cooperative zone or in the merge zone). After the ToC, the driver of the vehicle is in charge of the merging process. The ToC advice is sent using the *ToC advice* object defined in the *RSUSuggestedManeuverContainer* container of the MCM.

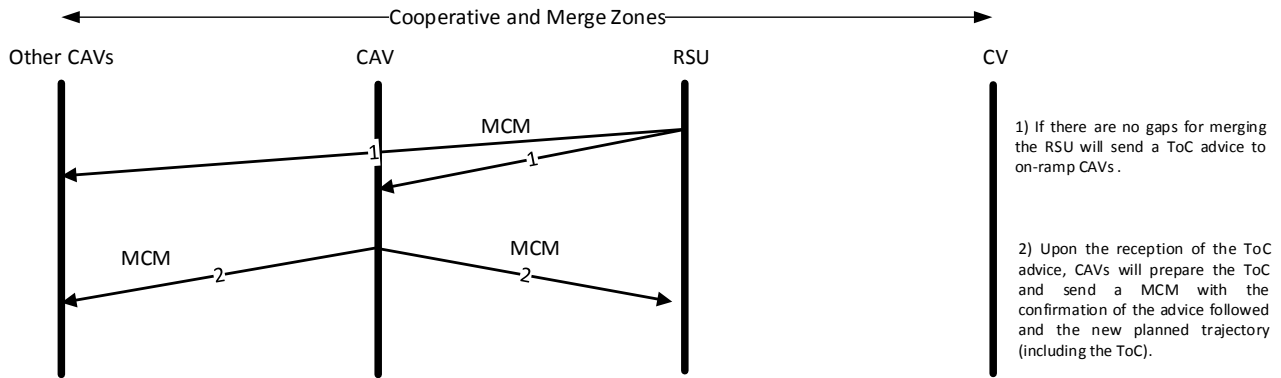


Figure 36. Message flow in the Cooperative and Merge Zones

3.2.4 Service 3: Prevent ToC/MRM by traffic separation

The interaction between automated and non-automated vehicles, especially at highway merge areas (see Figure 37), can create dangerous situations due to the unpredictable behaviour of human drivers. This can result in that CAVs need to perform a ToC or MRM. However, CAVs' drivers who are allowed to be involved in secondary driving tasks can find it hard to perform a ToC. To avoid these situations, Service 3 defines a traffic separation policy that places automated and manually driven vehicles at different lanes in order to minimize the lateral vehicle interactions at the merge area and thus reduce the number of ToCs.

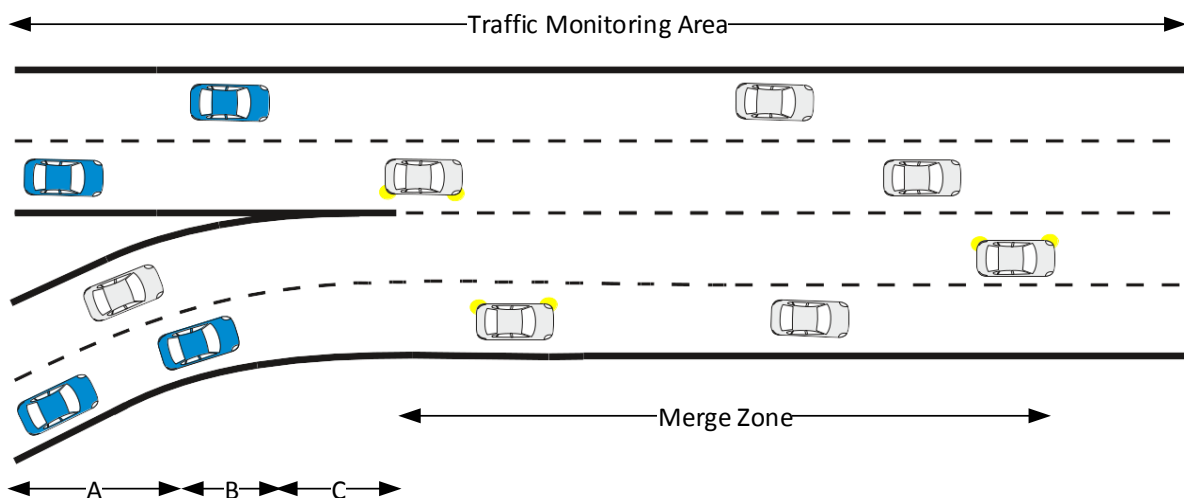


Figure 37. Scenario layout of Service 3 (A is the Traffic Separation Area, B the Transition Area and C the MRM Zone).

The traffic management logic of Service 3 is defined in the Deliverable 4.2 [5]. The TMC monitors the vehicles that enter the Traffic Monitoring Area (TMA) to determine which vehicles need to perform a lane change following the traffic separation policy. The TMC sends lane change advices to the identified vehicles that need to perform the lane change once they enter the Traffic Separation Area (zone A in Figure 37). The lane change advice includes the *triggering point of ToC* field (see Deliverable 5.1) which defines the position where the CAV should trigger a ToC if the advice has not been followed. In this scenario, the *triggering point of ToC* is defined as the start position of the Transition Area. If a CAV reaches the Transition Area (zone B in Figure 37) without performing the necessary lane change, a ToC will be initiated, and eventually an MRM at the beginning of the MRM Zone (zone C in Figure 37) if the ToC fails. This is done in order to assure that the traffic separation policy is fulfilled by all vehicles. Thus, complex interactions in the merge area between manually and automated driving vehicles are avoided reducing the risk of ToCs and/or MRMs in the merge area. Note that, a MRM in the merge area will disrupt both traffic streams. Hence, it is preferable to perform the ToCs/MRMs upstream of the merge zone to minimize the disruption of the traffic streams.

The following message flow describes the sequence of messages that need to be exchanged between the vehicles and between the vehicles and the infrastructure in order to execute Service 3 in the scenario defined in Figure 37.

Using the CAM and CPM messages shown in Section 3.2.1, the TMC gathers information about the vehicles approaching the highway's merge area. If the TMC finds it necessary, it sends individual lane change advices to the C(A)V's that need to perform lane changes in order to follow the traffic separation policy (see Figure 38). The advices are sent when the C(A)V's are entering the Traffic Separation Area. The *lane change advice* object defined in the *RSUSuggestedManeuverContainer* container of the MCM is used to send these advices. Upon the reception of the advices, CAVs use their next MCM message to acknowledge that they are going to follow the lane change advice. Those CAVs that are requested to perform a lane change are in charge of finding a gap to merge to the proper lane. If the gap is found, the CAV informs its surrounding vehicles using an MCM message that includes the updated trajectory (i.e. lane change). If the CAV is not able to find a gap by itself, a cooperative manoeuvre will be triggered by the infrastructure (centralized approach) or by the vehicle (distributed approach). Section 3.3 details the message flow employed for executing a cooperative manoeuvre.

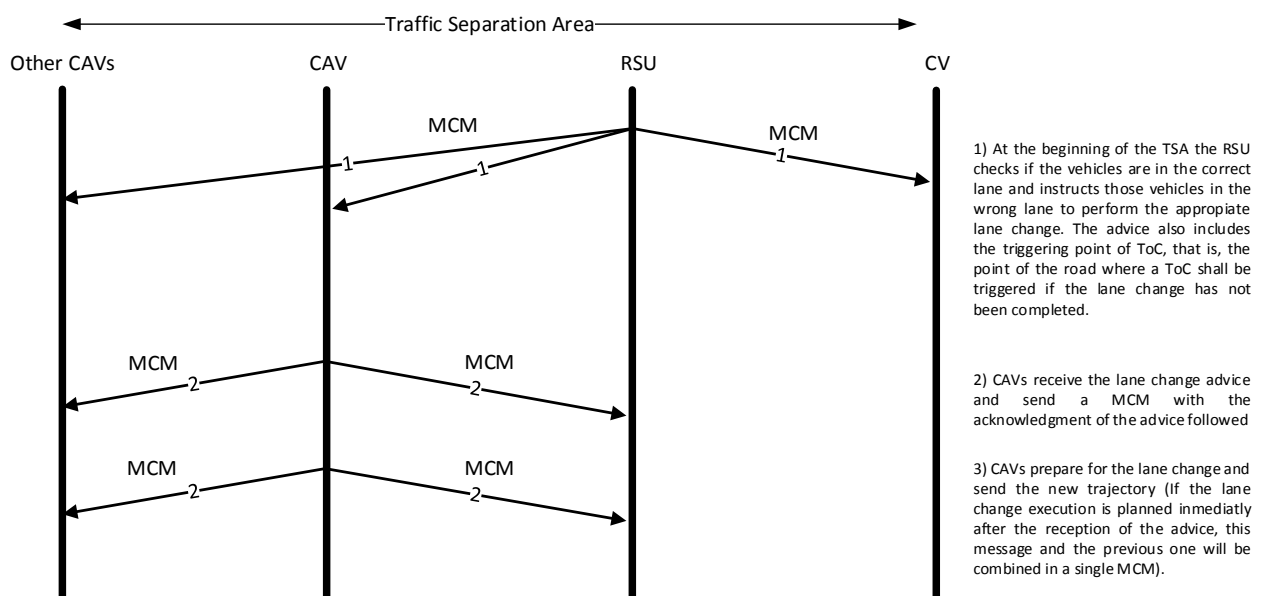
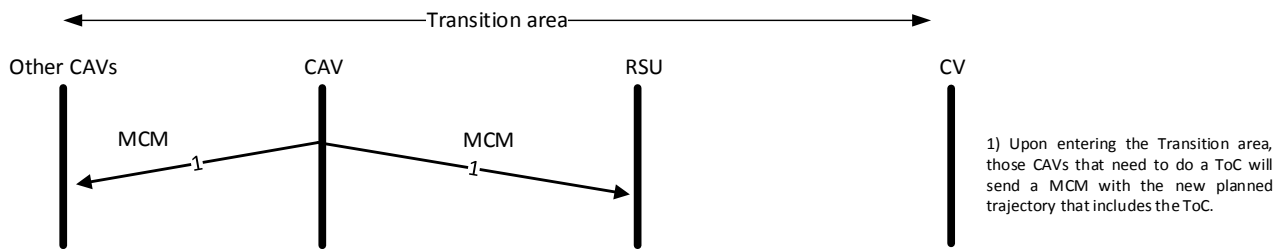
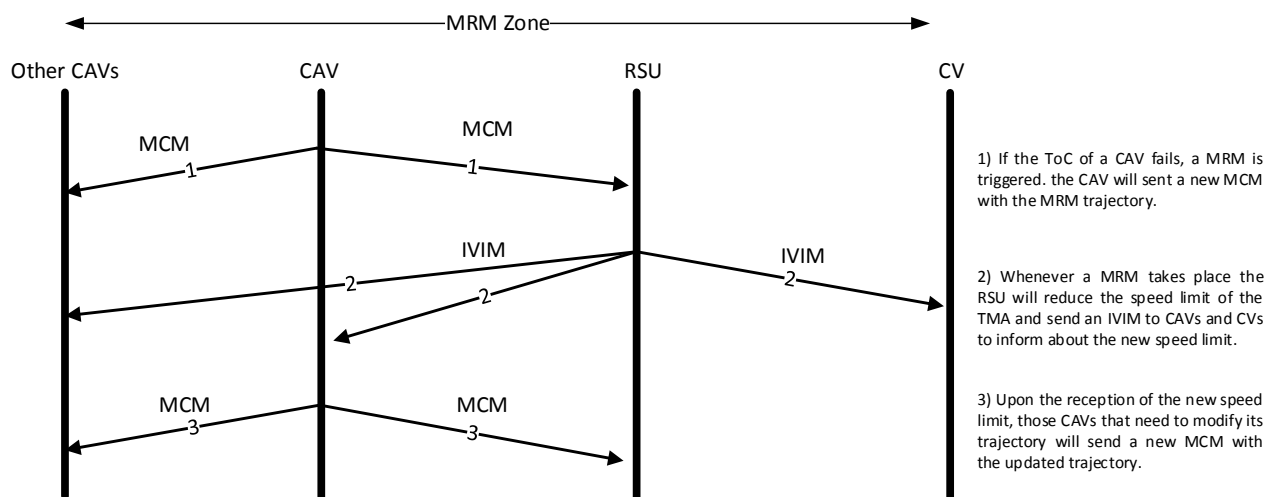


Figure 38. Message flow in the Traffic Separation Area.

Figure 39 shows the message flow in the Transition Area. CAVs entering the Transition Area but not driving in the lane assigned to CAVs will trigger a Take-over Request (ToR) to the driver of the vehicle. These CAVs will then continue driving in the same lane as manually driven vehicles. This action will trigger the transmission of an MCM message including the ToC trajectory in order to inform the surrounding CAVs and RSUs.

**Figure 39. Message flow in the Transition Area.**

If the ToC of a CAV fails, the CAV will trigger an MRM at the start of the MRM zone. The initiation of an MRM triggers the transmission of an MCM with the MRM trajectory. The TMC will be informed by the MCM of the MRM taking place. Then, it will reduce the speed limit of the scenario for the sake of safety. C(A)Vs will be informed about the new speed limit by the reception of an IVIM message. Upon the reception of the IVIM message, those CAVs that need to adapt the current speed will send an MCM with the updated trajectory.

**Figure 40. Message flow in the MRM Zone.**

3.2.5 Service 4: Manage MRM by guidance to safe spot

Roadworks zones are expected to disrupt vehicle automation by inducing ToC (see Figure 41). After a ToC is triggered, the driver needs to obtain full situation awareness and then take-over the control of the vehicle. If the driver is not able to take control of the vehicle, an MRM is triggered and the vehicle will come to a full stop. In those situations, the TMC can guide the vehicles executing an MRM to a predefined safe spot in order to reduce the impact in the traffic flow and

safety. In Figure 41, the critical distance indicates the minimum distance that a CAV needs to perform a lane change and an MRM before reaching the roadworks.

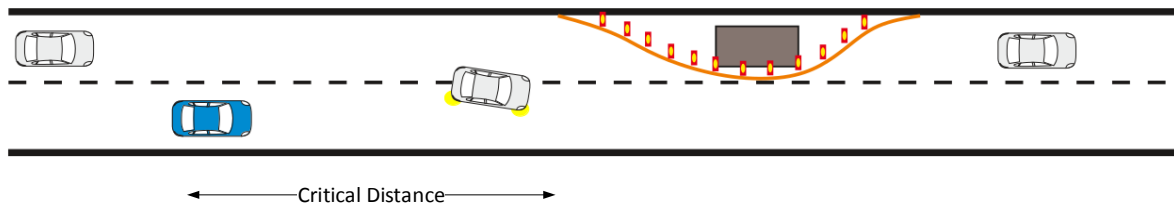


Figure 41. Scenario layout of Service 4.

The traffic management logic of Service 4 is defined in the Deliverable 4.2 [5]. In this scenario the TMC monitors the area around the roadworks zone and defines the location(s) to be used as safe spot(s). If an MRM takes place, the TMC guides the CAV to the safe spot by sending speed and lane change advices.

The following message flow describes the sequence of messages needed to execute Service 4 in the scenario defined in Figure 41. First of all, the TMC alerts vehicles upstream of the critical distance (see Figure 41) about the presence of the roadworks zone blocking the road and the existence of safe spots. This information is transmitted employing the *RoadWorksContainerExtended* container of the DENM and the MAPEM, respectively, by modifying the *LaneAttributes* of the *Road segment* of the safe spots as parking and stopping lanes. Then, the TMC monitors the scenario and looks for vehicles which need to do a ToC. The CAVs that need to perform a ToC will inform the TMC and surrounding CAVs by sending an MCM that includes the ToC trajectory. Upon reception of this MCM, the TMC will check if the CAV is in the closed lane (the lane blocked by the roadworks) or in the free lane, and if the distance between the roadworks and the CAV is sufficient to accommodate the whole ToC duration and the MRM (i.e. higher than the critical distance). If the CAV is driving in the closed lane upstream of the critical distance, the TMC will reserve the safe spot and guide the CAV accordingly if the ToC fails (see Figure 42). In case of ToC failure, the TMC will send an MCM message with a *car following advice* object as defined in the *RSUSuggestedManeuverContainer* container of the MCM. When the CAV receives the advice, it will update its trajectory. The new trajectory of the CAV is to execute an MRM that ends at the safe spot. The CAVs inform about this new trajectory by sending a new MCM message.

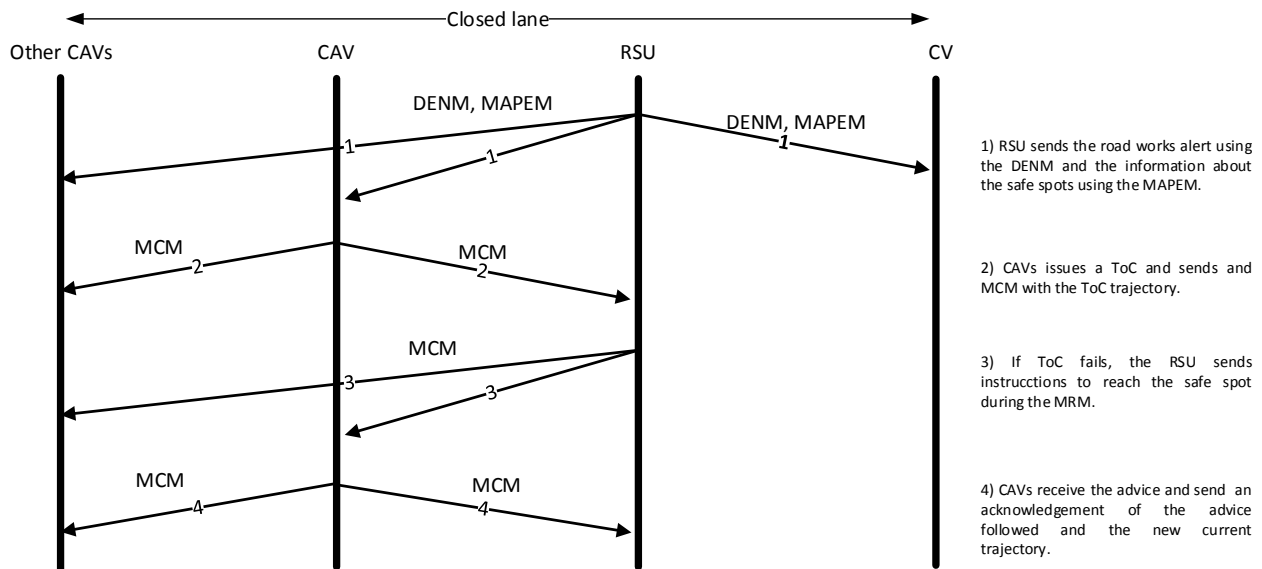


Figure 42. Message flow in the Closed lane (upstream of the critical distance).

The whole ToC and MRM cannot be performed if the distance of the CAV to the road works is shorter than the critical distance (see Figure 43). In this case if the driver does not take over control of the vehicle within a critical time window, the TMC will send an MRM advice to the CAV to ensure that there is sufficient space for accommodating the MRM in a safe way. This will be done employing the *ToC advice* object defined in the *RSUSuggestedManeuverContainer* container of the MCM.

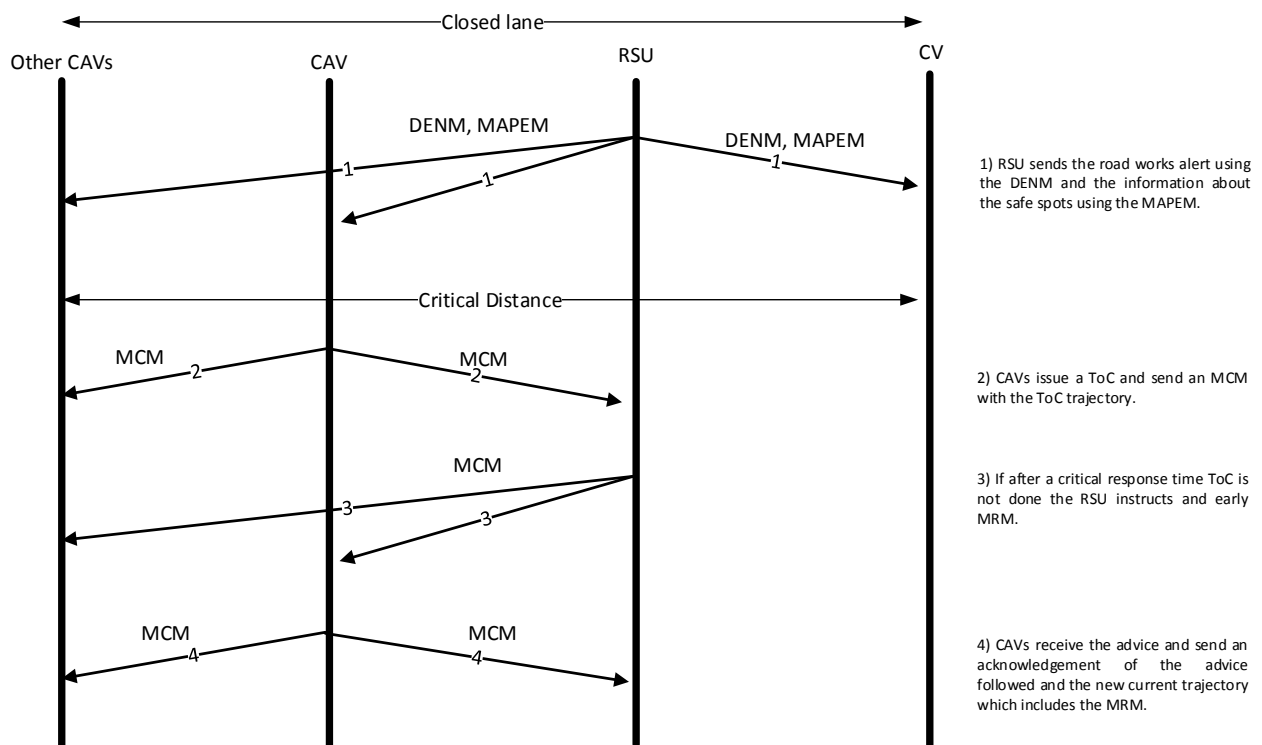


Figure 43. Message flow in the Closed lane (inside the critical distance).

When the CAV that performs the ToC is driving in the free lane upstream of the critical distance, the vehicle will need to perform a lane change in order to reach the safe spot (see Figure 44). Upon the reception of the MCM with the ToC information, the TMC will compute the trajectory necessary for the CAV to reach the safe spot. If the ToC fails, the TMC will send a lane change advice employing the *RSUSuggestedManeuverContainer* of the MCM. The CAV will receive the message and update its trajectory accordingly. This will trigger the transmission of a new MCM by the CAV which will include the acknowledgement of the advice followed and the new trajectory. If the CAV cannot execute the lane change, the TMC will check if there are nearby CAVs and it will send a *car following advice* to those CAVs in order to create a gap for the merge of the CAV performing the MRM. Again, this is done employing the *RSUSuggestedManeuverContainer* container of the MCM.

Finally, if a CAV is driving in the free lane and it is located at a distance to the roadworks shorter than the critical distance, there is no enough space for the execution of the lane change and the MRM. Thus, the TMC will not provide any advice and the CAV will perform a MRM in the free lane.

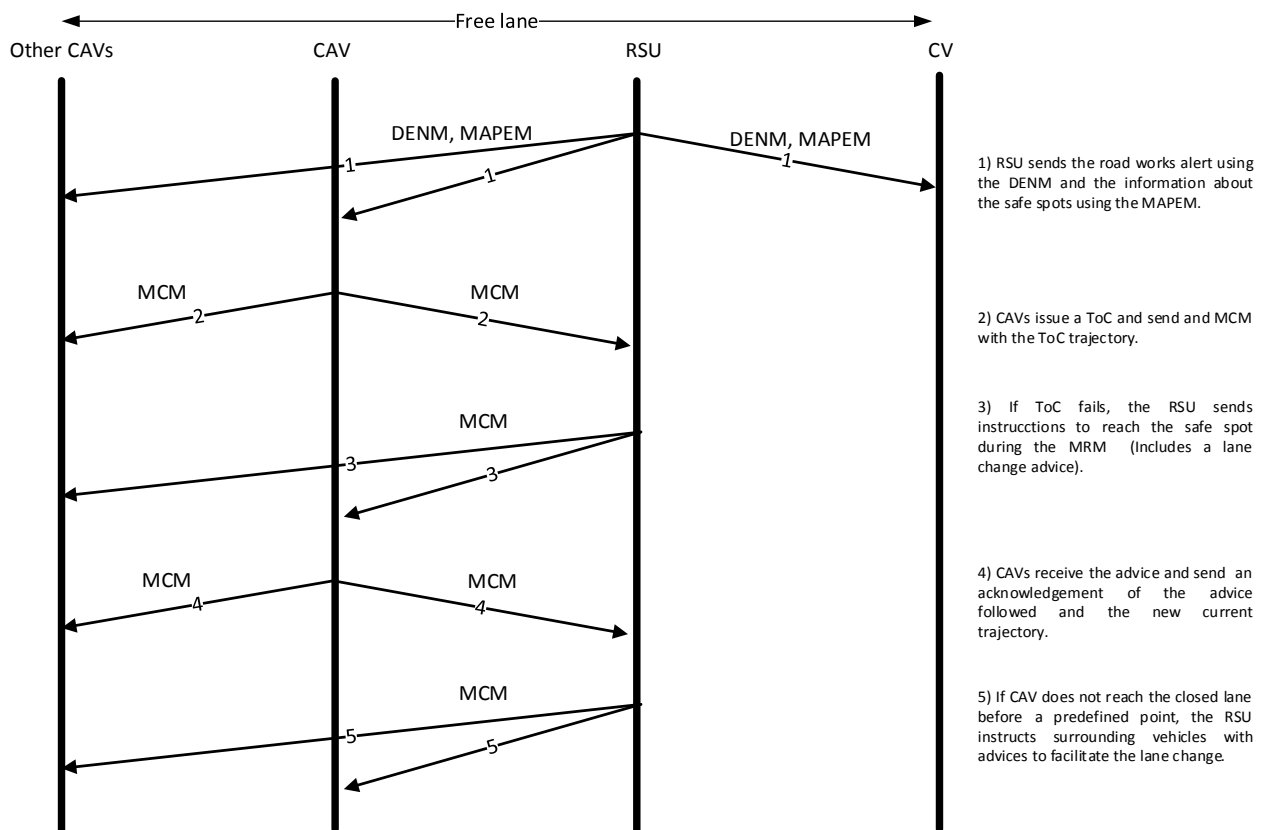


Figure 44. Message flow in the Free lane (upstream of the critical distance).

3.2.6 Service 5: Distribute ToC/MRM by scheduling ToCs

The automated driving is not allowed in specific traffic areas due to external reasons (see Deliverable 2.2). In these situations, CAVs must perform a ToC upstream of the No-automated-driving zone (No-AD zone) (see Figure 45). This can generate a high number of ToCs in the same area, which can lead to adverse effects for the traffic safety and efficiency. Service 5 aims at

distributing the ToC in time and space over a large area in order to increase the overall traffic safety and efficiency.

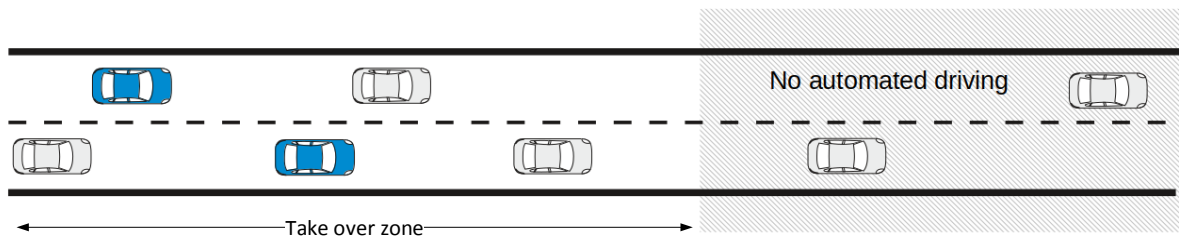


Figure 45. Scenario layout of Service 5.

The traffic management logic of Service 5 is defined in the Deliverable 4.2 [5]. In this scenario, the TMC monitors the area upstream of the No-AD-zone and computes a desirable position for the upcoming ToCs of the approaching CAVs. Using this information, the TMC sends individual ToC advices to the CAVs in order to guarantee that all CAVs are manually driving once they enter in the No-AD zone.

The following message flow describes the sequence of messages needed to execute the traffic management procedures of Service 5.

First, the TMC sends an alert to upcoming C(A)Vs to inform them about the presence of the No-AD zone. This alert is sent using the DENM message as defined in the Deliverable 5.1. Further, the TMC monitors the area upstream of the No-AD zone identifying the CAVs and computing desirable positions for the ToC of each CAV. In order to initiate the takeover, the TMC uses the MCM to send individual ToC advices to the CAVs as defined in the *RSUSuggestedManeuverContainer* container. The reception of the MCM messages triggers that CAVs execute the ToC. Also, the CAVs send an MCM that includes the acknowledgement of the advice followed and the updated trajectory. This updated trajectory includes the preparation of the ToC measures (i.e. increased headway) and the information about the ToC.

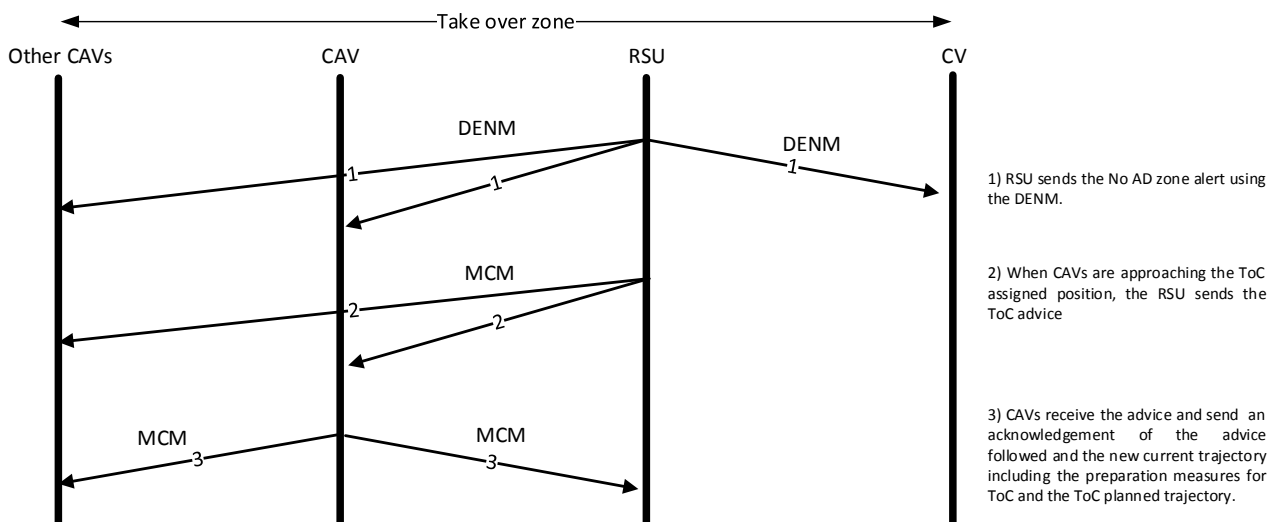


Figure 46. Message flow upstream of the No AD zone.

3.3 Cooperative lane changes at Transition Areas

The traffic management logic of the TransAID services requires the execution of cooperative lane changes in order to facilitate the lane change of CAVs. The execution of a cooperative lane change is based on a mutual agreement on the trajectories of different CAVs. Thus, V2X communications are necessary in order to define the cooperative trajectories of vehicles. In a cooperative lane change there are three different actors (see Figure 47): the ego-vehicle, the target leader and the target follower. The ego-vehicle is the vehicle that wants to execute the lane change. The target leader and target follower are the vehicles ahead and behind, respectively, of the CAV (i.e. the ego-vehicle) once the lane change is executed (see Figure 47). It is important to note that in the TransAID project, a cooperative lane change only modifies the trajectories of the ego-vehicles and the target follower (see the Deliverable 3.2 [61]).

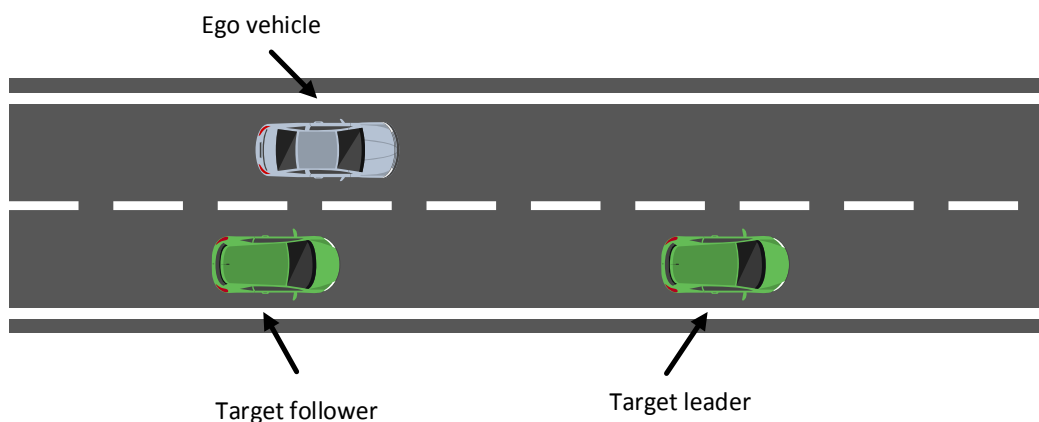


Figure 47. Cooperative lane change scenario.

The TransAID project defines two different approaches to address a cooperative lane change: centralized and distributed. In the centralized approach, the TMC manages the whole process and coordinates the trajectories of the ego-vehicle and the target follower in the execution of the cooperative lane change. Figure 48 shows the necessary message flow between the vehicles and the infrastructure in order to execute the centralized cooperative lane change. The process is based on the exchange of MCM messages between the TMC, the target follower and the ego-vehicle. First, the TMC sends a lane change advice to the ego-vehicle. If the ego-vehicle can perform the lane change advice by itself (e.g. if there is gap enough between the target leader and the target follower to allow a merge of the ego-vehicle), then no cooperation is needed. In this case, the ego-vehicle sends an MCM message that includes the new planned trajectory (i.e. the lane change) and the acknowledgement to the TMC to indicate that it is following the lane change advice. However, if it is not possible for the ego-vehicle to perform the lane change, the cooperation with other vehicles is needed. In that case, the TMC would detect that the ego-vehicle cannot perform the lane change (e.g. from the received CAM, MCM messages) and would send a gap creation advice to the target follower using the *car following advice* object defined in the *RSUSuggestedManeuverContainer* container of the MCM message. Upon the reception of the MCM, the target follower updates its trajectory in order to create the necessary gap to allow the merging of the ego-vehicle. The target follower announces the gap creation through the transmission of an MCM message that includes the acknowledgement of the advice followed and its new planned trajectory. Once the ego-vehicle detects that the target follower has created the gap, it updates its trajectory in order to perform the lane change. This lane change is announced in an MCM message that includes the new planned trajectory. Finally, the ego vehicle executes the lane change.

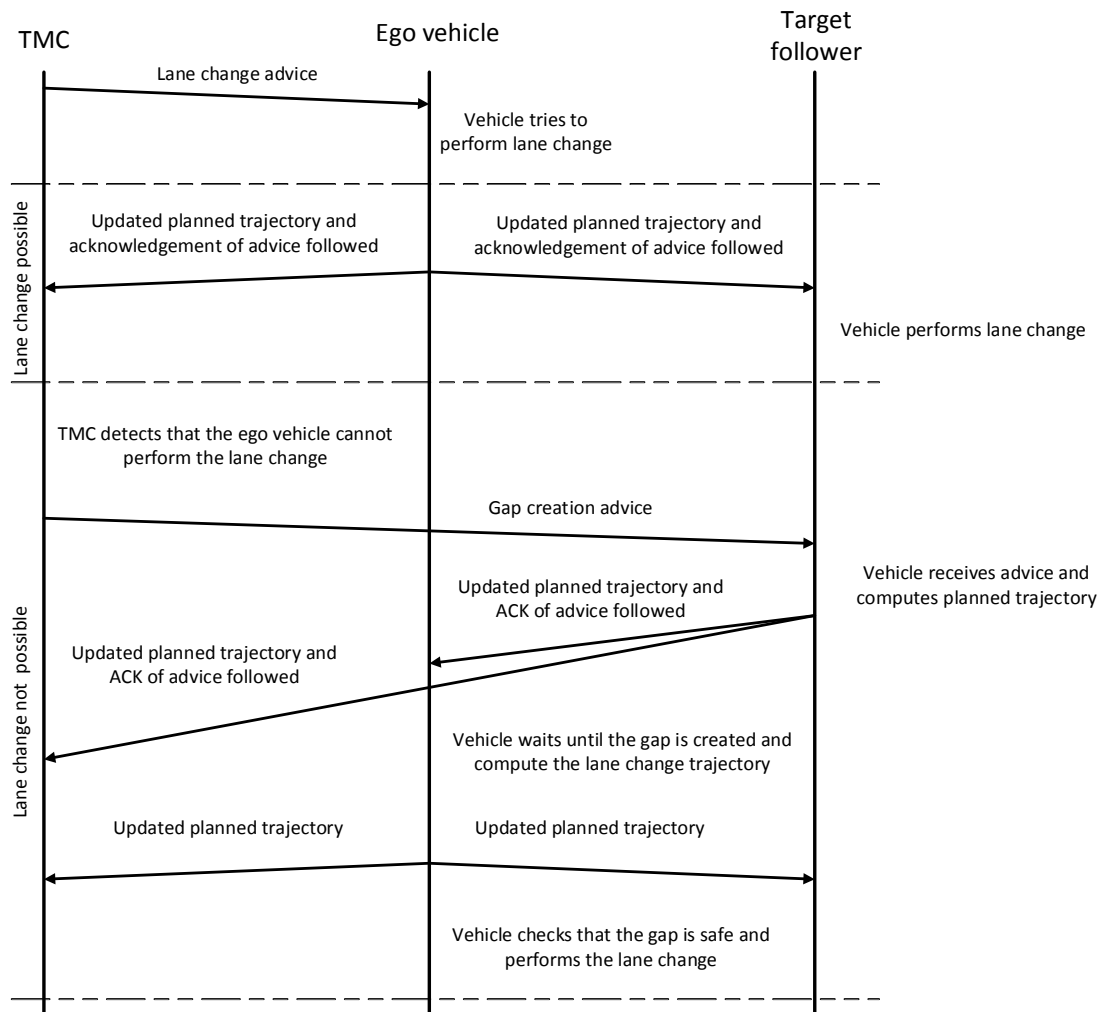


Figure 48. Message flow of a centralized cooperative lane change.

The message flow for the decentralized approach is shown in Figure 49. In this case, the cooperative manoeuvre is coordinated between the involved vehicles without the participation of the TMC. Again, the cooperative manoeuvre is triggered by the need of a CAV (i.e. the ego-vehicle) to perform a lane change. This can happen if the CAV receives an advice from the TMC or if the CAV needs to perform a lane change, for instance to overtake a slow vehicle. In the message flow depicted in Figure 49 we assume that CAV needs to perform a lane change because it has received any of the lane change advices defined in the TransAID services. Then, Figure 49 shows that the first message transmitted is a lane change advice by the TMC. However, the message flow that follows could be employed if the lane change is triggered by the ego-vehicle. Upon the reception of the lane change advice, the ego-vehicle tries to perform the lane change. If there is gap enough in between the target leader and the target follower (i.e. if it is possible to perform the lane change), the ego-vehicle sends an MCM message that includes an acknowledgement of the advice followed and the updated planned trajectory. If the ego-vehicle detects that it is not possible to perform the lane change, it will request cooperation to the other vehicles. This starts with the computation of the desired trajectory (i.e. the lane change) and the transmission of a new MCM with the planned and desired trajectories. Upon the reception of this MCM message transmitted by the ego-vehicle, the target follower updates its planned trajectory to create the gap the ego-vehicle

needs to merge. The creation of this gap by the target follower would trigger the transmission of an MCM that includes its updated planned trajectory. Upon the reception of this MCM message, the ego-vehicle infers that the cooperation has been accepted and thus, it updates its planned trajectory. Again, this triggers the transmission of a new MCM message by the ego-vehicle that includes the new planned trajectory (i.e. the one that includes the lane change). Finally, once the ego-vehicle detects that the gap created by the target follower is safe it performs the lane change.

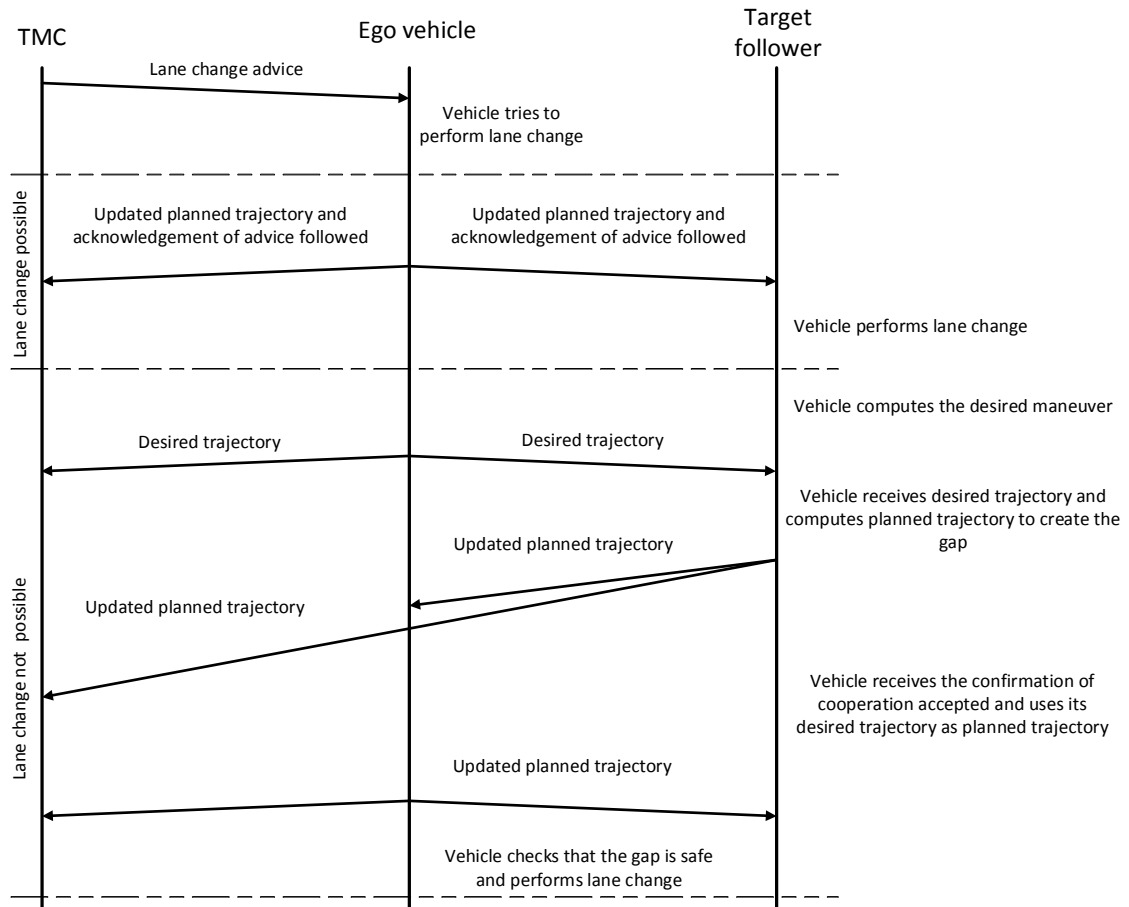


Figure 49. Message flow of a decentralized cooperative lane change.

3.4 Preliminary analysis of MCM generation rules

The previous sections have described the TransAID approach to coordinate manoeuvres of vehicles leveraging the support of the infrastructure, and have shown how this approach can be applied to the traffic management measures defined in the Services of the TransAID project. The TransAID approach seeks contributing to the ETSI's work item on Maneuver Coordination Service that focuses on coordinating the manoeuvres between vehicles by defining the format of the messages to be exchanged, including the MCM (see Deliverable 5.1 [4]), and their generation rules. The generation rules refer to conditions that trigger the transmission of an MCM, e.g. which vehicles should transmit an MCM and when they should transmit it. As shown in Section 2.3 for the collective perception service, the effectiveness of the manoeuvre coordination service highly depends on the correct design of the generation rules. In fact, MCM messages should be transmitted with a frequency high enough to guarantee that the vehicles' manoeuvre coordination is possible. However, a too frequent exchange of MCM messages can increase the channel load to the point that it can negatively impact the performance and scalability of the V2X network. The increase in the channel load can be particularly challenging if MCMs are transmitted in the reference control channel where other messages utilized to support active safety applications, such as the CAM or the

CPM, are transmitted. Note that, the increase of the channel load may result in higher packet collisions and communication latency, and therefore in a reduction of the V2X reliability. These effects can in turn degrade the effectiveness of the MCS.

In this section we analyse three different generation rules for the MCM. Two of them consider a periodic transmission of the MCM at 2Hz (i.e. every 0.5s) and 10Hz (i.e. every 0.1s). The third one is a dynamic generation rule where the MCM is transmitted when the absolute position of the originating vehicle changes by more than 4m or when the time elapsed since the last transmission of an MCM is 1 second. This approach is aligned with the one currently considered at ETSI for the transmission of CAMs [14].

In order to estimate the channel load generated by the different generation rules, we follow the analytical model presented in [62] to estimate the CBR (Channel Busy Ratio). The CBR represents the percentage of time that a vehicle senses the communications channel as busy. The analytical model presented in [62] estimates the CBR as a function of the traffic density (β , in vehicles/m), the message generation frequency (λ , in Hz), the message duration (T , in seconds), and the spatial integral of the packet sensing ratio (PSR):

$$CBR = \beta \cdot \lambda \cdot T \cdot \int_d PSR(d) \quad (1)$$

PSR is defined as the probability of sensing a packet at a given distance. This probability is computed as the probability that a vehicle situated at a given distance from the transmitter obtains a received signal power higher than the carrier sense threshold. Equation (1) assumes that vehicles are uniformly distributed and that there are no packet collisions. Two packets collide when they are (partially) transmitted in the same time interval, thus, the amount of time that the channel is busy during a collision is lower than the amount of time required to successfully transmit two packets. Therefore, taking collisions into account would result in a reduction of the CBR estimated using equation (1). In particular, the reduction factor can range from 10% to 20% when the CBR varies from 0.3 to 0.6, approximately, according to previous studies such as [63] and [64]. Thus, the CBR estimated using equation (1) can be considered as an upper bound of the real CBR.

Figure 50 plots the CBR as a function of the traffic density per lane for the three message generation rules and for three traffic scenarios: urban, rural and motorway. The configuration parameters of the traffic scenarios (urban, rural and motorway) are extracted from the Deliverable 3.1 [65] and summarized in Table 7. For the three scenarios a straight road segment with different lanes (see Table 7) is considered. The results reported in this section also consider that the size of the MCM is 300 bytes and the size of the CAM is 200 bytes. In addition, the Winner+ B1² model is utilized to model the propagation losses [66]. The message generation frequency for the dynamic policy has been computed using the well-known Van Aerde model [67] that relates traffic intensity, traffic density and speed. This model has been used to obtain the relationship between the traffic density and the speed following the parameters shown in Table 7.

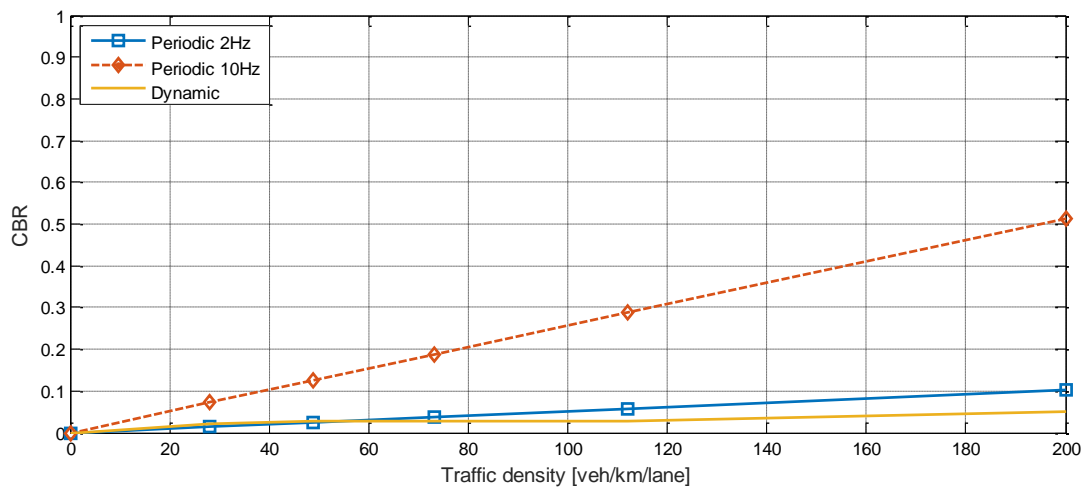
² The same channel model is employed for the three traffic scenarios. Future work will take into account the effects of different channel models.

Table 7. Parameters for the different traffic scenarios

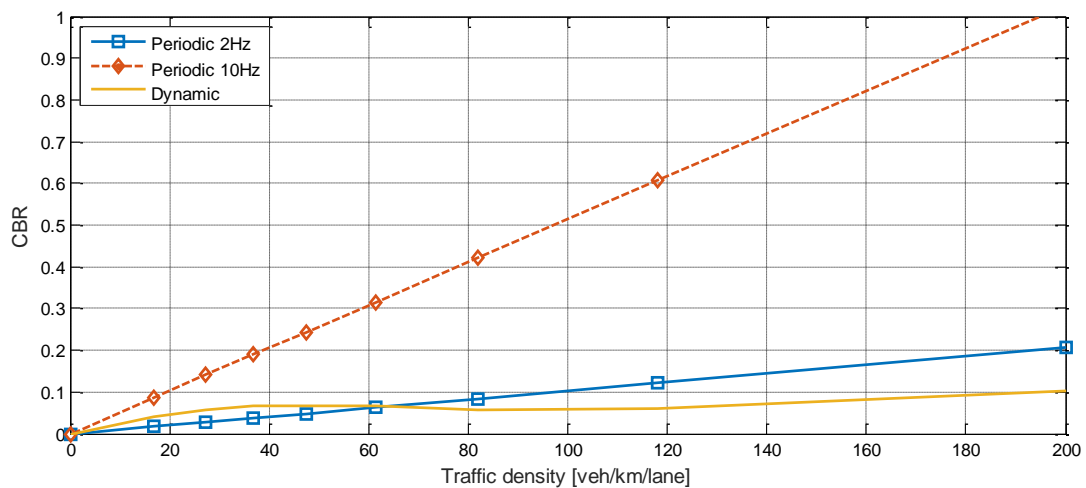
Scenario	Number of lanes	Capacity	Maximum Speed	Maximum density
Urban	1	1500 vehicles/hour/lane	50km/h	200 vehicles/km/lane
Rural	2	1900 vehicles/hour/lane	80 km/h	200 vehicles/km/lane
Motorway	3	2100 vehicles/hour/lane	120 km/h	200 vehicles/km/lane

Figure 50 shows that the periodic message generation rules do not scale well with the density since the CBR linearly increases with the traffic density. In this analysis, we compare the CBR as a function of the traffic density per lane in order to compare scenarios with a similar level of traffic congestion. It should be noted that scenarios with more lanes with the same level of congestion will accommodate a different number of vehicles. For example, a three-lane motorway can accommodate more vehicles than a one-lane urban road with the same level of congestion. If we focus on the periodic policies, the CBR increases linearly with the number of vehicles on the scenarios, thus the motorway scenario shows a higher CBR than the rural or urban scenarios. On the other hand, the dynamic policy adapts the message generation frequency to the vehicles' speed. Thus, when the traffic density per lane increases and more vehicles are transmitting MCMs, the transmission period is reduced because vehicles move slower. As a result, the CBR reduces. However, this effect stops when vehicles are moving slower than 4 m/s, at this point, the MCM is transmitted every second. If we compare the different scenarios, we can see an increase in the CBR in the scenarios with higher speeds and more lanes for two reasons: 1) there are more vehicles in the scenario and 2) vehicles move at higher speeds and thus transmit MCM more frequently. The results reported in Figure 50 show that transmitting MCM at 10Hz generates the highest channel load in the three scenarios while it is unclear whether generating an MCM every 0.5s (periodic policy at 2Hz) is sufficient for a safe and efficient coordination of the manoeuvres. The dynamic policy adapts the transmission rate to the speed of vehicles and hence it can be scaled to higher traffic density scenarios. However, as in the case of the low period approach, the dynamic policy should be carefully designed in order to fully allow the safe execution of cooperative manoeuvres.

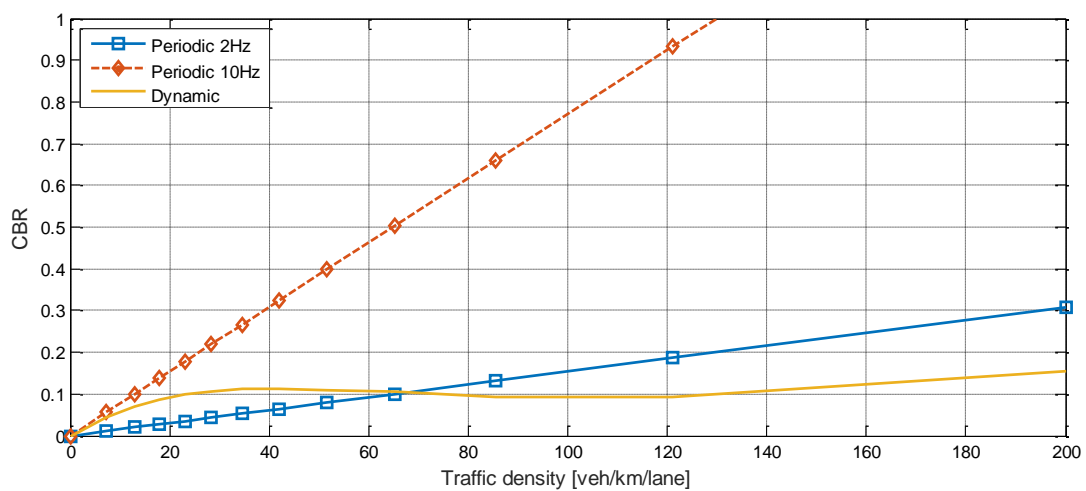
The previous analysis highlights the interest for dynamic message generation rules that take into account the vehicular context. However, further research is needed to define the message generation rules. For example, rather than continuously (with a fixed or dynamic frequency) generating MCMs, more advanced policies might also consider additional factors like the detection (through CAMs or CPMs) of a new vehicle (or object) or the anticipation of required change of trajectory. In addition, it is also necessary to analyse whether MCMs should co-exist on the reference control channel with CAMs (or beacons) and other existing messages, or whether multi-channel schemes should be considered to reduce the risk of channel congestion.



a) Urban scenario



b) Rural scenario

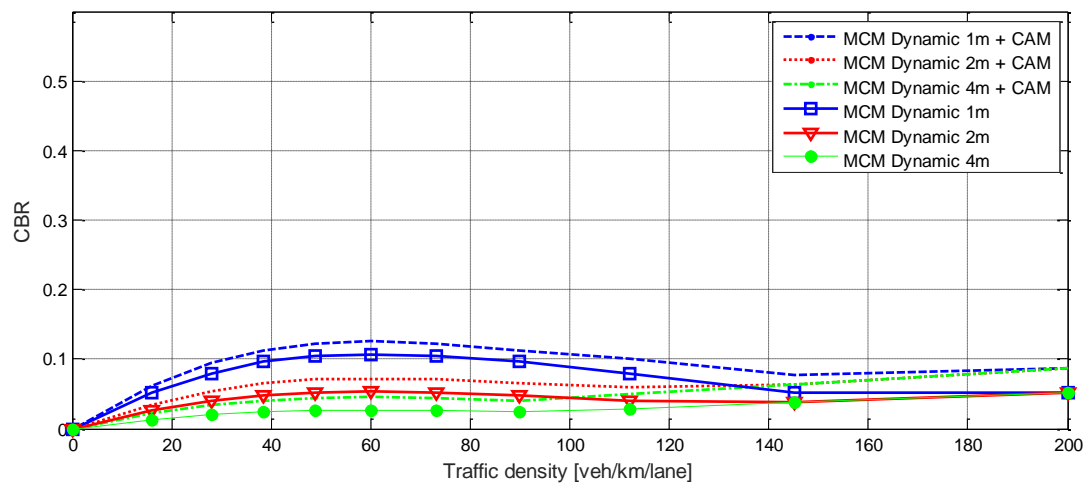


c) Motorway scenario

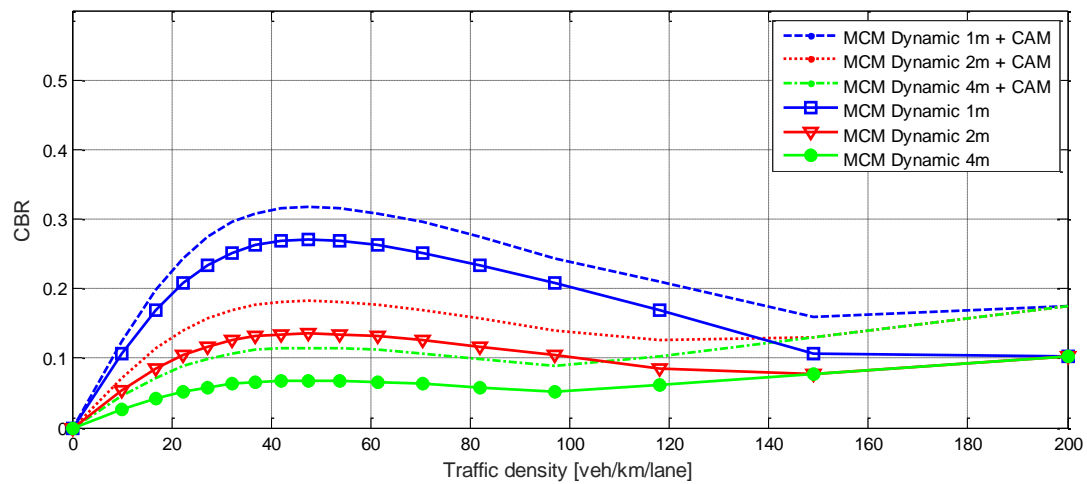
Figure 50. Channel Busy Ratio as a function of the traffic density for three different MCM generation rules (no CAM messages in the scenarios).

Figure 51 shows the CBR when the CAM and MCM co-exist in the same channel for the three different scenarios. Both the MCM and CAM generation follows a dynamic generation rule. For the CAM this policy is set as defined in the standard [14], i.e. a CAM is transmitted when the absolute position of the originating vehicle changes by more than 4m or when the time elapsed since the last CAM transmission is 1 second. On the other hand, different dynamic policies have been tested for the generation of the MCM. In particular, the MCM is transmitted when the absolute position of the generating vehicle changes more than 1m (*MCM dynamic 1m* in Figure 51) 2m (*MCM dynamic 2m* in Figure 51) and 4m (*MCM dynamic 4m* in Figure 51). Again, in all these dynamic policies the MCM is transmitted also if the time elapsed since the last MCM is one second. If we focus on the motorway scenario of Figure 51.c, we can observe how the CBR increases for the dynamic policies which transmit MCMs more frequently. Furthermore, we can also observe the increase in the channel load generated by the coexistence of CAMs and MCMs in the same channel. Similar trends are observed for the other two traffic scenarios. The coexistence of the CAM and MCM in the reference control channel can reach higher levels of channel load at higher density scenarios if the dynamic policy transmits MCM too frequent. Thus, it is necessary to further study the effects of the coexistence of messages on the same channel in terms of channel load.

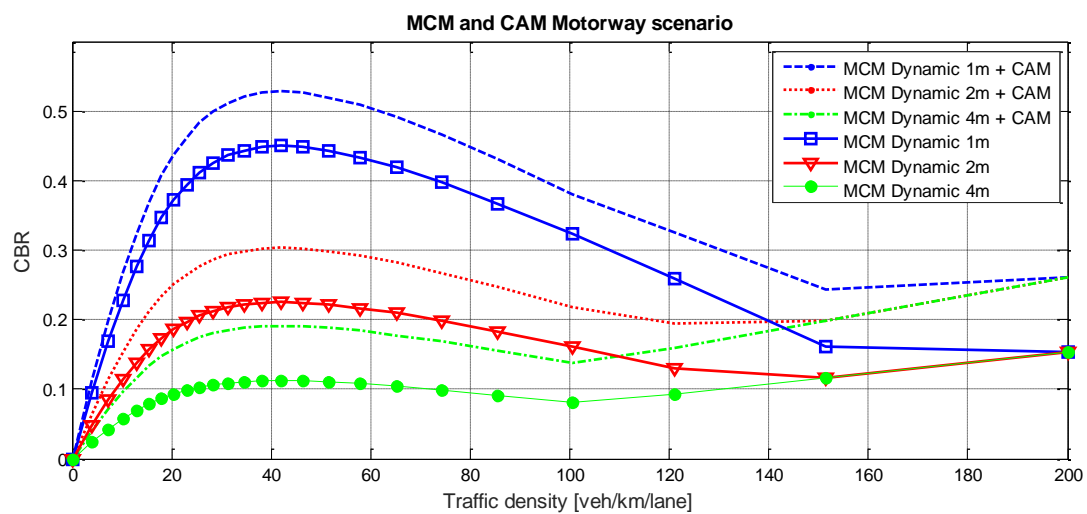
This section has shown the need to define appropriate generation rules for the Maneuver Coordination Service that allow a safe execution of the cooperative manoeuvres without compromising the wireless channel load. In the second iteration of the TransAID project we will further investigate the effects of different generation rules in the V2X communications employing advanced traffic and communications simulators such as SUMO and NS-3. Based on this analysis, an appropriate set of message generation rules will be defined in order to complete the definition of the Maneuver Coordination Service described in this Deliverable and Deliverable 5.1 [4].



a) Urban scenario



b) Rural scenario



c) Motorway scenario

Figure 51. Channel Busy Ratio for the MCM transmission on the urban, rural and motorway scenario.

4 Conclusions

The TransAID project aims at designing traffic management measures for transition areas with mixed traffic scenarios where LV, CV and CAV coexist. Within this context, a key aspect of the TransAID project is to demonstrate how V2X communications can be utilized to allow the cooperation of connected and automated vehicles, leveraging the support of the infrastructure, and to enable their safe coexistence with other conventional and connected vehicles. The cooperation between connected and automated vehicles is addressed in TransAID through the cooperative sensing and cooperative manoeuvres following, and actively contributing, to the ETSI's work items 'DTR/ITS-00183' on collective perception service (CPS) and 'DTS/ITS-00184' on maneuver coordination service (MCS), respectively.

This document has thoroughly analysed the existing works and standardization efforts (especially at ETSI) on cooperative sensing and cooperative driving. As part of the cooperative sensing, this document has also reviewed the available sensors in vehicles and infrastructures and existing techniques to fuse the data these sensors generate. Then, specific sensor fusion techniques that are being developed under TransAID to cope with the challenges that the services defined in TransAID raise. In particular, models to support the merging assistant and techniques to perform the sensor fusion at the vehicle are presented. In addition, this document has presented an in-depth evaluation of the CPM message and the different rules that are being considered at ETSI to generate CPM messages. These rules define which objects should be transmitted in a CPM, and how often they should be transmitted. The conducted analysis has shown the existing trade-off between perception capabilities and communications performance (and network scalability). The conducted analysis has shown that the CPM generation policies that improve the perception capabilities generate higher channel load levels and hence have a higher risk to saturate the communications channel and render the network unstable. While some redundancy could benefit the detection of nearby objects, unnecessary redundancy could severely impact the performance of vehicular networks. The dynamic policy that is currently being considered at ETSI to support the CPM generation achieves an interesting balance between perception capabilities and communications performance. However, it is yet an open discussion whether the observed levels of redundancy are necessary or whether they could be further optimized to reduce any potential negative impact of the implementation of CPM in the stability and scalability of future V2X networks. These aspects are to be analysed during TransAID's second iteration.

Regarding the cooperative driving, this document has introduced the TransAID's proposal to extend the current manoeuvre coordination approach under discussion at ETSI that gives to the road infrastructure the opportunity to support manoeuvre coordination under certain scenarios and conditions. The benefits of the TransAID proposal are discussed, and a detailed analysis of how this proposal can be applied to the Services identified in TransAID is presented. For each of these Services, the message flow required to coordinate the manoeuvres between C(A)Vs is defined. A key message to enable cooperative driving is the MCM that is currently being defined at ETSI. As part of the efforts that TransAID is devoting to contribute to the MCS, this document has also performed an initial analysis of the generation rules for the MCM. The conducted analysis has highlighted the interest in utilizing dynamic MCM generation rules that take into account the vehicular context. Further investigations on the MCM generation rules to achieve an efficient implementation of cooperative manoeuvres from a communications perspective will be conducted during the TransAID's second iteration.

The impact of this deliverable on TransAID can be summarized as follows. The message flow described in this document together with the description of the message format included in Deliverable 5.1 complete the definition of the V2X message set and communication protocols of the first iteration of the TransAID project. This directly contributes to the achievement of the sub-

objective 4 of the project. Similarly, the sensor fusion algorithms included in this document that enhance the detection of conventional vehicles and obstacles on the road contribute to the achievement of the sub-objective 5 of the project. The message flow described in this document will be integrated in WP6 into the iTETRIS platform in order to evaluate on a simulation platform the traffic management procedures defined in WP4 together with the analysis of the performance of the communications protocols defined in WP5. In addition, the V2X message set defined in WP5 will be included in the real world tests developed in WP7.

References

- [1] A. Wijnnga, et al., “Use cases and safety and efficiency metrics”, *TransAID Deliverable D2.1*, March 2018.
- [2] E. Jakobsson, et al., “Function description and requirements”, *HAVEit Deliverable D11.1*, Sept. 2008.
- [3] L. Lücken, et al. “An integrated platform for the simulation and the assessment of traffic management procedures in Transition Areas”, *TransAID Deliverable D6.1*, Oct. 2018.
- [4] M. Rondinone, et al., “Definition of V2X message sets”, *TransAID Deliverable D5.1*, Aug. 2018.
- [5] S. Maerivoet, et al., “Preliminary simulation and assessment of enhanced traffic management measures”, *TransAID Deliverable D4.2*, Jan. 2019.
- [6] E. Mintsis, et al., “Cooperative maneuvering in the presence of hierarchical traffic management”, *TransAID Deliverable D3.2*, Feb. 2019.
- [7] H. J. Powell, et al., “Vehicle-to-vehicle communications: Readiness of V2V technology for application” , *National Highway Traffic Safety Admin., Washington, DC, USA, Tech. Rep. DOT HS 812 014*, Aug. 2014.
- [8] J. Chang, “Summary of NHTSA heavy-vehicle vehicle-to-vehicle safety communications research”, *National Highway Traffic Safety Admin., Washington, DC, USA, Tech. Rep. DOT HS 812 300*, Jul. 2016.
- [9] K. Sjöberg, et al., "Cooperative Intelligent Transport Systems in Europe: Current Deployment Status and Outlook", *IEEE Vehicular Technology Magazine*, vol. 12, no. 2, pp. 89-97, June 2017.
- [10] R. Molina-Masegosa and J. Gozalvez, "LTE-V for Sidelink 5G V2X Vehicular Communications: A New 5G Technology for Short-Range Vehicle-to-Everything Communications", *IEEE Vehicular Technology Magazine*, vol. 12, no. 4, pp. 30-39, Dec. 2017.
- [11] S. Kim, et al., "Multivehicle Cooperative Driving Using Cooperative Perception: Design and Experimental Validation", *IEEE Transactions on Intelligent Transportation Systems*, vol. 16, no.2, pp. 663-680, Apr. 2015.
- [12] H. Günther, et al., "Realizing collective perception in a vehicle", *Proc. IEEE Vehicular Networking Conference (VNC)*, pp. 1-8, Columbus, OH, USA, 8-10 Dec. 2016.
- [13] Schindler, J. et al., “System architecture for real world vehicles and road side”, *TransAID Deliverable D7.1*, June 2018.
- [14] ETSI ITS, "Intelligent Transport Systems (ITS); Vehicular Communications; Basic Set of Applications; Part 2: Specification of Cooperative Awareness Basic Service", *EN 302 637-2 V1.3.2*, 2014.
- [15] Y. Bar-Shalom, P. K. Willet and T. Xin, “Tracking and Data Fusion”, Storrs, CT: YBS publishing, 2011.
- [16] A. Elfes, “Using Occupancy Grids for Mobile Robot Perception and Navigation”, *Computer*, vol. 22, no. 6, pp. 46-57, June 1989.
- [17] S. Thrun, W. Burgard and D. Fox, “Probabilistic Robotics”, Cambridge, MA: MIT press, 2005.
- [18] I. J. Cox and S. L. Hingorani, “An efficient implementation of Reid's multiple hypothesis tracking algorithm and its evaluation for the purpose of visual tracking”, *IEEE Transactions on Pattern Analysis and Machine Intelligence*, vol. 18, no. 2, pp. 138-150, Feb. 1996.

- [19] R. P. Mahler, “Statistical Multisource-Multitarget Information Fusion”, Norwood, MA: Artech House, Inc., 2007.
- [20] R. P. Mahler, “Advances in Statistical Multisource-Multitarget Information Fusion”, Norwood, MA: Artech House, Inc., 2014.
- [21] D. Bharanidhar, S. Tilo and W. Christian, “Track Level Fusion Algorithms for Automotive Safety Applications”, *Proc. IEEE International Conference on Signal Processing Image Processing & Pattern Recognition (ICSIPR)*, pp. 179-184, Coimbatore, India, 7-8 Feb. 2013.
- [22] M. Rondinone, et al., “ADAS functions and HD map”, *MAVEN Deliverable D5.2*, July 2018.
- [23] B. Mourllion, et al., “Collaborative perception for collision avoidance”, *Proc. IEEE International Conference on Networking, Sensing and Control*, vol.2, pp. 880-885, Taipei, Taiwan, 21-23 March 2004.
- [24] N. Karam, F. Chausse, R. Aufrere and R. Chapuis, “Cooperative Multi-Vehicle Localization”, *Proc. IEEE Intelligent Vehicles Symposium*, pp. 564-570, Tokyo, Japan, 13-15 June 2006.
- [25] A. Rauch, et al., “Analysis of V2X communication parameters for the development of a fusion architecture for cooperative perception systems”, *Proc. IEEE Intelligent Vehicles Symposium (IV)*, pp. 685-690, Baden-Baden, Germany, 5-9 June 2011.
- [26] H. Günther, et al., “Collective perception and decentralized congestion control in vehicular ad-hoc networks”, *Proc. IEEE Vehicular Networking Conference (VNC)*, pp. 1-8, Columbus, USA, 8-10 Dec. 2016.
- [27] H. Günther, et al., “The Effect of Decentralized Congestion Control on Collective Perception in Dense Traffic Scenarios”, *Computer Communications*, vol 122, Pages 76-83, June 2018.
- [28] ETSI ITS, “Intelligent Transport Systems (ITS); Decentralized Congestion Control Mechanisms for Intelligent Transport Systems operating in the 5 GHz range; Access layer part”, *TS 102 687*, 2018.
- [29] ETSI ITS, “Intelligent Transport Systems (ITS); Access layer specification for Intelligent Transport Systems in the 5 GHz frequency band”, *EN. 302 663*, 2013.
- [30] L. Hobert, et al., “Specifications for the enhancement to existing LDM and cooperative communication protocol standards”, *AutoNet2030 Deliverable D3.2*, Feb. 2015.
- [31] M. Fanaei, A. Tahmasbi-Sarvestani, Y.P. Fallah, G. Bansal, M.C. Valenti, and J.B Kenney, “Adaptive content control for communication amongst cooperative automated vehicles”, *Proc. IEEE 6th International Symposium on Wireless Vehicular Communications (WiVeC)*, pp. 1-7, Vancouver, Canada, 14-15 Sept. 2014.
- [32] S. M. O. Gani, et al., “A Study of the Effectiveness of Message Content, Length, and Rate Control for Improving Map Accuracy in Automated Driving Systems”, *IEEE Transactions on Intelligent Transportation Systems*, vol. 20, no. 2, pp. 405-420, Feb. 2019.
- [33] Y. Wang, et al., “Performance and Scaling of Collaborative Sensing and Networking for Automated Driving Applications”, *Proc. IEEE International Conference on Communications Workshops (ICC Workshops)*, pp. 1-6, Kansas City, USA, 20-24 May 2018.
- [34] ETSI ITS, “Intelligent Transport System (ITS); Vehicular Communications; Basic Set of Applications; Analysis of the Collective Perception Service (CPS)”, *TR. 103 562 V0.0.15*, 2019.
- [35] ETSI ITS, “Intelligent Transport Systems (ITS); Users and applications requirements; Part 2: Applications and facilities layer common data dictionary”, *TS 102 894-2 V1.2.1*, 2014.
- [36] ETSI ITS, “Intelligent Transport System (ITS); Vehicular Communications; Basic Set of Applications; Facilities layer protocols and communication requirements for infrastructure services”, *TS 103 301 V1.1.1*, 2016.

- [37] J. Huang, et al., “Speed/accuracy trade-offs for modern convolutional object detectors”, *Proc. IEEE Conference on Computer Vision and Pattern Recognition*, pp. 3296-3297, Honolulu, HI, USA, 21-26 July 2017.
- [38] TensorFlow Object Detection. Online: https://github.com/tensorflow/models/blob/master/research/object_detection/g3doc/detection_model_zoo.md
- [39] A. Geiger, et al., “Vision meets robotics: The KITTI dataset”, *The International Journal of Robotics Research*, vol. 32, no. 11, pp. 1231-1237, Aug. 2013.
- [40] E. Rosten, R. Porter and T. Drummond, “Faster and better: A machine learning approach to corner detection”, *IEEE transactions on pattern analysis and machine intelligence*, vol. 32, no. 1, pp. 105-119, Jan. 2010.
- [41] J.-Y. Bouguet, “Pyramidal implementation of the affine lucas kanade feature tracker, description of the algorithm”, Intel Corporation, 2001.
- [42] T. Kroeger, et al, “Fast optical flow using dense inverse search”, *Proc. European Conference on Computer Vision*. pp. 471-488, Amsterdam, The Netherlands, 8-16 Oct. 2016.
- [43] L. Zhang, Y. Li, R. Nevatia, “Global data association for multi-object tracking using network flows”, *Proc. IEEE Conference on Computer Vision and Pattern Recognition*, pp. 1-8, Anchorage, AK, USA, 23-28 June 2008.
- [44] J. Berclaz, et al., “Multiple object tracking using k-shortest paths optimization”, *IEEE Transactions on Pattern Analysis and Machine Intelligence*, vol. 33, no. 9, pp. 1806-1819, Sept. 2011.
- [45] P.J. Besl and N.D. McKay, “Method for registration of 3-D shapes”, *IEEE Transactions on Pattern Analysis and Machine Intelligence*, vol. 14, no. 2, pp. 239-256, Feb. 1992.
- [46] A. Houenou, et al., “A track-to-track association method for autonomous perception systems”, *Proc. of IEEE Intelligent Vehicles Symposium (IV)*, pp. 704-710, Alcala de Henares, Spain, 3-7 June 2012.
- [47] 3rd Generation Partnership Project (3GPP), Technical Specification Group Radio Access Network; “Study on LTE-based V2X Services”, *TR 36.885 V14.0.0*, 2016.
- [48] Caltrans Performance Measurement System (PeMS), California Department of Transportation data-set, U.S.State. Available at [last accessed on 2019-01-16]: <http://pems.dot.ca.gov/>.
- [49] M. Sepulcre and J. Gozalvez, “Coordination of Congestion and Awareness Control in Vehicular Networks”, *Electronics*, vol. 7, no. 11, 335, Dec. 2018.
- [50] A. Wijnenga, et al., “Scenario definitions and modelling requirements”, *TransAID Deliverable D2.2*, Feb. 2018.
- [51] Z. Lu., R. Happee, C.D.D. Cabral, M. Kyriakidis, and J.C.F. de Winter, “Human factors of transitions in automated driving: A general framework and literature survey”, *Transportation Research Part F: Traffic Psychology and Behaviour*, vol. 43, pp. 183-198, Nov. 2016.
- [52] A. Correa, et al., “Management of Transitions of Control in Mixed Traffic with Automated Vehicles”, *Proc. 16th International Conference on Intelligent Transportation Systems Telecommunications (ITST)*, pp. 1-7, Lisboa, Portugal, 15-17 Oct. 2018.
- [53] L. Hobert, A. Festag, I. Llatser, L. Altomare, F. Visintainer and A. Kovacs, “Enhancements of V2X communication in support of cooperative autonomous driving”, *IEEE Communications Magazine*, vol. 53, no. 12, pp. 64-70, Dec. 2015.
- [54] A. Kesting, M. Treiber, and D. Helbing, “General lane-changing model mobil for car-following models”, *Transportation Research Record: Journal of the Transportation Research Board*, vol. 1999, pp. 86-94, Jan. 2007.

- [55] L. Hobert, “Cooperative ITS facilities for automated driving”, *ETSI ITS WG1 standardization meeting*, Sophia Antipolis, France, 14 April 2015.
- [56] C. Englund, et al., “The Grand Cooperative Driving Challenge 2016: boosting the introduction of cooperative automated vehicles,” *IEEE Wireless Communications*, vol. 23, no. 4, pp. 146-152, Aug. 2016.
- [57] Unifying Control and Verification of Cyber-Physical Systems (UnCoVerCPS). Project website [last accessed on 2019-01-16]: <https://cps-vo.org/group/UnCoVerCPS/>
- [58] Distributed Cooperative Human-Machine Systems (DCoS). Project website [last accessed on 2019-01-16]: <https://artemis-ia.eu/project/27-d3cos.html>
- [59] B. Lehmann, H. J. Günther and L. Wolf, “A Generic Approach towards Maneuver Coordination for Automated Vehicles,” *Proc. IEEE 21st International Conference on Intelligent Transportation Systems (ITSC)*, pp. 3333-3339, Maui, Hawaii, USA, 4-7 Nov. 2018.
- [60] ETSI ITS, “Intelligent Transport Systems (ITS); Vehicular Communication; Informative Report for the Maneuver Coordination Service”, *TR 103 578 V0.0.2* (2018-10), (Draft)
- [61] E. Mintsis, et al., “Cooperative manoeuvring in the presence of hierarchical traffic management”, *TransAID Deliverable D3.2*, Feb. 2019.
- [62] M. Sepulcre, J. Gozalvez and B. Coll-Perales, “Why 6 Mbps is Not (Always) the Optimum Data Rate for Beaconing in Vehicular Networks”, *IEEE Transactions on Mobile Computing*, vol. 16, no. 12, pp. 3568-3579, Dec. 2017.
- [63] Q. Chen, D. Jiang, T. Tielert, and L. Delgrossi, “Mathematical Modeling of Channel Load in Vehicle Safety Communications”, *Proc. IEEE Vehicular Technology Conference (VTC Fall)*, pp. 1-5, San Francisco, CA, USA, 5-8 Sept. 2011.
- [64] G. Bansal, and J. B. Kenney, “Controlling Congestion in Safety- Message Transmissions: A Philosophy for Vehicular DSRC Systems”, *IEEE Vehicular Technology Magazine*, vol. 8, no. 4, pp. 20-26, Dec. 2013.
- [65] E. Mintsis, et al., “Modelling, simulation and assessment of vehicle automations and automated vehicles’ driver behaviour in mixed traffic”, *TransAID Deliverable D3.1*, Aug. 2018.
- [66] METIS Consortium, “Initial channel models based on measurements”, *ICT-317669-METIS/D1.2*, April 2014.
- [67] M. Van Aerde, “Single regime speed-flow-density relationship for congested and uncongested highways”, *Proc. 74th TRB Annual Conference*, Washington DC, USA, 27 Jan. 1995.

Annex A: List of contributions to V2X standardization and specification

- 1) A. Correa et al. (University Miguel Hernandez of Elche), participation at the ETSI ITSWG1-Maneuvering Coordination Service drafting session, 26 February 2018: Introducing TransAID objective and focus for possible MCS service application.
- 2) A. Correa et al. (University Miguel Hernandez of Elche), participation at the ETSI ITSWG1-Maneuvering Coordination Service drafting session, 18 October 2018: Challenges and solutions for maneuver coordination.
- 3) M. Sepulcre et al. (University Miguel Hernandez of Elche), participation at the ETSI ITSWG1-Collective Perception Service drafting session, 23 January 2019: Simulation Study on Collective Perception.
- 4) M. Rondinone et al. (Hyundai Motor Europe Technical Center), “Transition Areas for Infrastructure Assisted Driving”, presentation at the C2C-CC Working Group Roadmap meeting, 19 June 2018: Introducing the TransAID services and scenarios for consideration in the C2C-CC roadmapping
- 5) A. Correa et al. (University Miguel Hernandez of Elche), “V2X for transition of control in cooperative automated driving”, presentation at the C2C-CC Forum, 21 November 2018: